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THE ENGLISH ELECTRIC JOURNAL

Contents

Page 3: SOME NOTES ON WIND TUNNEL DRIVES *by W. E. Streete, A.R.Ae.S., Assoc.I.E.E.*

11: "ENGLISH ELECTRIC" EQUIPMENT IN THE WIDE HOT STRIP MILL OF JOHN SUMMERS & SONS LTD., SHOTTON, NR. CHESTER *by G. R. Wilson, B.Sc., A.M.I.E.E., Chief Engineer, Metal Industries Division.*

19: STATISTICAL METHODS APPLIED TO ELECTRICAL INSULATION *by E. Jones, B.Sc.(Eng.), M.I.E.E., A.M.I.Mech.E., Assoc.A.I.E.E., Chief Insulation Engineer.*

28: THE PROTECTION OF GAS TURBINE AIR INTAKES AGAINST SAND AND ICE *by C. L. Cowdrey, F.R.Ae.S., M.S.A.E., Chief Installation Engineer, D. Napier and Son, Ltd., Experimental Establishment, Luton.*

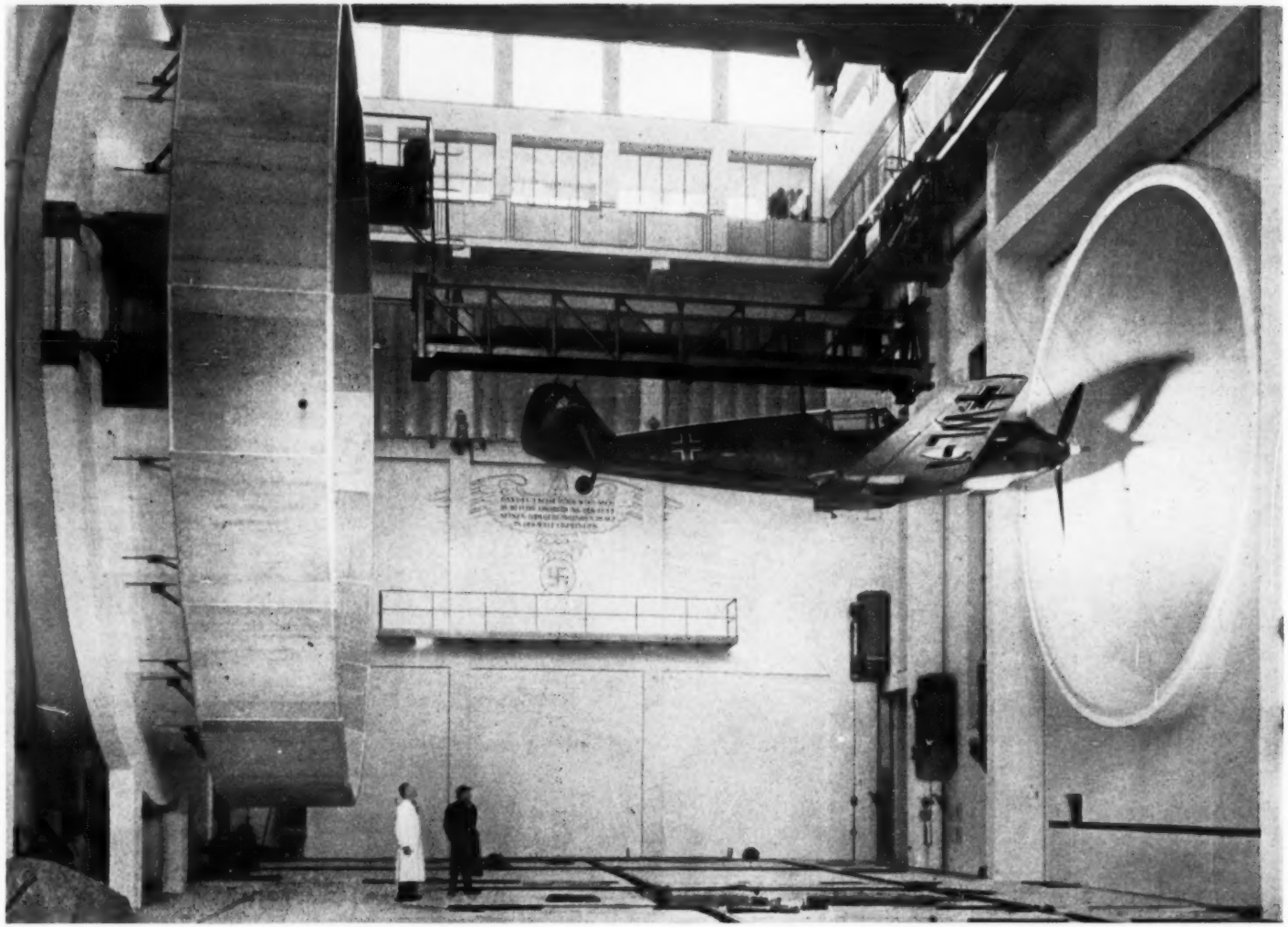
Editorial

ONE OF THE FIRST occasions that Wind Tunnel equipment has been dismantled and transported from one country to another occurred after the war when a team of experts visited Germany on behalf of the Ministry of Works. Among the experts was Mr. W. E. Streete, Manager of the Plant Sales section of The English Electric Company, who is now for the first time able to give us details of equipment used in Germany over a period of years for testing aircraft and the flying bomb.

Incorporated into his article is information on equipment manufactured by the Company and details of plant in America and Australia.

In Germany the English Electric Company's team, under the direction of Mr. Streete, took a leading part in the investigation of the German electrical equipment and its subsequent dismantling and packing, and the organisation is now concerned with re-installation of part of the plant. This is regarded as a major engineering project of which little has hitherto been heard.

All communications respecting Editorial Contents should be addressed to The Editor, THE ENGLISH ELECTRIC JOURNAL, THE ENGLISH ELECTRIC COMPANY LIMITED, STAFFORD, ENGLAND.



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Frontispiece. Large open jet type wind tunnel at Volkenrode showing German aircraft about to undergo test.

Some Notes on Wind Tunnel Drives.

By W. E. STREETE, A.R.Ae.S., Assoc. I.E.E.

GREATER INTEREST IN Wind Tunnels has undoubtedly been stimulated by the advent of the gas turbine applied to the propulsion of aircraft.

The higher aircraft speeds now possible as well as the development of rockets and guided missiles, stresses the need for intensive research on scaled down models.

Attention has also been drawn to this subject by discoveries made after the conclusion of the last war, when British scientists and engineers were able to examine and operate wind tunnels found in Germany.

The English Electric Company was privileged to take part in this examination and towards the end of 1945 a team of engineers was sent out in fulfilment of a contract with the Ministry of Works, Engineering Division, to examine, record and report on the electrical equipments installed at various research establishments, but primarily those at Volkenrode near Brunswick. The German name for this establishment was Luftfahrforschungsanstalt usually contracted to L.F.A.

The records of the electrical equipments found on the site were incomplete and not always in accordance with the actual installations so that it was necessary for completely new diagrams to be prepared.

Progress of Wind Tunnels

The human race has for many centuries experimented with flight, but it is probably true to say that only through the use of wind tunnels has man learned to fly.

The history of wind tunnels in the modern sense dates from 1903 when the Wright brothers in America built a box 22 in square by 5 ft long, in which model aircraft were inserted and air blown past them at about 27 miles an hour. It was as the result of these experiments that the Wright brothers were able to build the aeroplane which left the ground.

This elementary wind tunnel contained the basic idea of modern tunnels, of holding a model stationary and blowing air past it at a speed equivalent to moving the model through still air.

The basis of the comparison of tests obtained on models in wind tunnels with those obtained in full-scale flight is the Reynolds number, and the extent of the compressibility effect is known as the

$$\text{Mach. number } M = \frac{\text{air speed}}{\text{speed of sound.}}$$

The Reynolds number is proportional to the air density, the air velocity and the scale of the model, but inversely proportional to the viscosity of the air.

Thus a designer has, in theory, a difficult choice to make ; since to obtain a given Reynolds number he can either raise the density of the air in the tunnel above atmospheric pressure, hence high density and variable density tunnels, or increase the air speed or increase the scale of the model.

All these alternatives have the effect of increasing the initial cost of the tunnel and also the power required for the drive.

The designer is therefore faced with the necessity of deciding within the terms of his financial and constructional facilities the limits he can accept on the factors referred to above.

In the case of supersonic work, it has been common practice to employ what are known as intermittent tunnels as a method of reducing the cost. With this type of tunnel, a pressure vessel is evacuated or pressurised and by means of a quick acting valve, the air is allowed to flow into or out of the vessel through the working section of the tunnel.

Clearly the time for which the high velocity air can flow depends on the size of the vessel and of the working section, but in any case special arrangements are necessary for taking readings in

the short time available. The availability of this type of tunnel is low since there must inevitably be an interval between tests.

An example of this type of tunnel was found at Volkenrode, employing a spherical pressure vessel of 30 ft or more in diameter. This vessel was evacuated by a 1,500 h.p. motor-driven exhauster and the working section of the tunnel could either be 0.4 × 0.4 metres or 0.6 × 0.3 metres.

The air speed through the smaller of the working sections was equal to a Mach. number of 3 but the duration of the flow of air was under 30 seconds and the time taken to re-evacuate the sphere was between 3 and 4 minutes.

The exhauster was driven by a 750 volt D.C. motor, which is now fed from a new 1,000 kW pumpless steel bulb rectifier equipment supplied by the English Electric Company. This type of tunnel is not suitable for subsonic work and the following remarks are therefore based on the continuous design.

Continuous tunnels can be of the open jet type (see frontispiece) with the working section an open space between the nozzle and the collector, or of the closed return circuit type, but the electrical problems are similar in both cases. The closed type of continuous tunnel has now almost superseded the open jet type as the former requires only about half the power of the latter for the same size of tunnel with the same air speed.

The fundamental principles of the majority of wind tunnels are firstly, the ability to vary the air speed flowing over the model through a wide range—this range may be as high as 10 to 1 in the case of subsonic work—and secondly, the need to maintain any selected speed constant within fine limits.

Vertical Spinning Tunnel

Variable air speed is most usually and conveniently obtained by varying the speed of the fan, but examples exist of tunnels fitted with variable pitch propellers. This arrangement simplifies the electrical driving equipment since it enables a constant speed motor to be used. This can therefore be of the A.C. synchronous type, or alternatively, a change pole induction motor can be used depending on the range of speed required.

A vertical spinning tunnel using a variable pitch fan is now under construction in this country, for which The English Electric Company are building a 1,500 h.p. 500 r.p.m. vertical spindle synchronous induction motor designed for use on a 11,000 volts 3-phase 50-cycle supply.

A feature of a vertical spinning tunnel is the ability to maintain the spinning model stationary

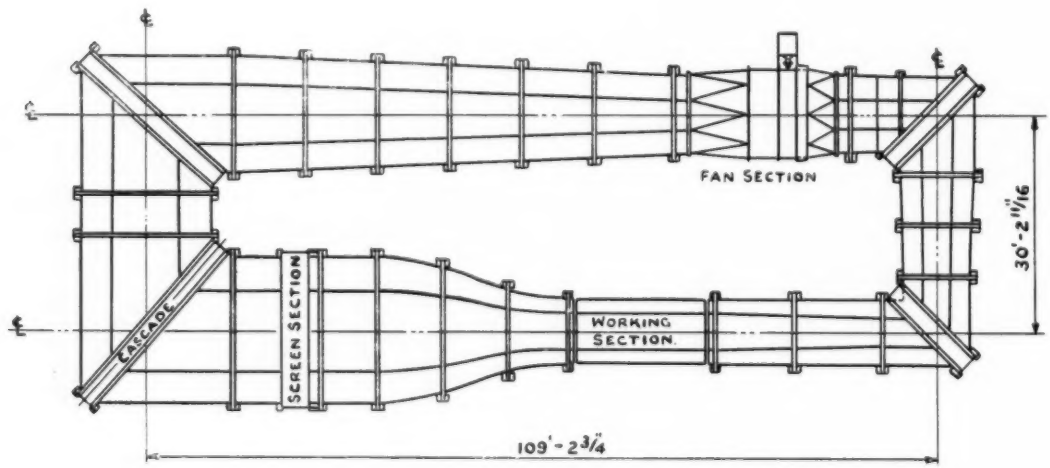

Fig. 1. Typical subsonic closed return circuit wind tunnel.

Fig. 2. Working section and operating platform of the "English Electric" wind tunnel at Warton. The balance control desk is seen in the foreground.

in space against the up current of air so that it can be observed from an observation room in the side of the tunnel. Rapid changes of air speed are necessary to keep the model within observable limits and pitch changing provides a ready and economical means of meeting this requirement.

The type of drive to be employed for a wind tunnel depends primarily on the nature of the research work to be carried out. If this is to be limited to subsonic work then a multi-blade fan is normally used with a wide range of speed.

For supersonic work it is usual to employ a rotary compressor, and in some examples it has been possible to build the compressor casing as part of the tunnel circuit.

Multi-bladed fans for small and medium subsonic tunnels are usually made of wood and it is undesirable for the tip speed of such fans greatly to exceed 500 ft/sec. as the noise becomes excessive. Moreover, if the tip speed approaches the speed of sound the losses become prohibitive.

This limit fixes the diameter, or the speed of the fan, but since for a given working section dimensions and air speed, the diameter of the fan is based on the general design of the tunnel, there is not much latitude in the fan speed in r.p.m.

Warton Wind Tunnel

A variable speed D.C. motor is ideal for this type of drive and a typical example is the 9 ft × 7 ft working section subsonic wind tunnel designed, built and installed by The English Electric Company at their aerodrome at Warton, Lancashire.

The following information regarding this tunnel is taken from the paper written by Mr. D. L. Ellis, Deputy Chief Engineer of the Aircraft Division of The English Electric Company and published in the August, 1949, issue of the Journal of the Royal Aeronautical Society. The author acknowledges his thanks to Mr. Ellis and to the Society for permission to reproduce this information.

This tunnel is of the general purpose low turbulence type with a designed air speed of 200 ft/sec. Fig. 2 shows its working section and operating platform.

The fan is 12 ft in diameter and runs at 695 r.p.m. maximum speed, giving a tip speed of about 440 ft/sec.

The driving motor has a two-hour rating of 250 h.p. and is mounted outside the tunnel. It is coupled to the fan through a bevel gear box, the latter being mounted in the fan nacelle. The drive from the motor to the gear box is by means of a flexibly coupled shaft which passes through one of the nacelle supports.

This arrangement permits the use of a motor

speed of 1,500 r.p.m. giving a smaller and cheaper motor than if direct coupled to the fan. It has the great advantage of avoiding the special construction required with a nacelle mounted motor.

The motor is supplied from a Ward Leonard motor generator set, the driving motor of the latter being of the synchronous induction type. The fan motor has a speed range of 10 to 1 obtained by armature voltage control, the field of the D.C. generator being supplied from two thyratrons arranged as a full wave rectifier. This arrangement was adopted to comply with the requirements of automatic control obtained from a manometer operated by the tunnel pressure.

A complete electronic system was designed and was eventually developed to give a sensitivity of less than 0.1 per cent. of the top speed of the motor. Manual operation is also available and a current limiting device restricts the motor torque to 130 per cent. of full load during acceleration and deceleration. This value cannot be exceeded by rough handling of the controls.

The inherent advantage of the Ward Leonard system as applied to wind tunnel drives is that A.C. voltage variations cannot be reflected through to the D.C. motor, and this and the use of a synchronous driving motor for the converting set both contribute towards the maintenance of constant motor speed for a given generator field setting. Moreover, regenerative braking is inherent in the scheme.

Australian Research

A larger but similar drive was supplied by The English Electric Company to a research establishment in Australia, a few years ago. Fig. 3 is a view of the working section and control desk for this tunnel.

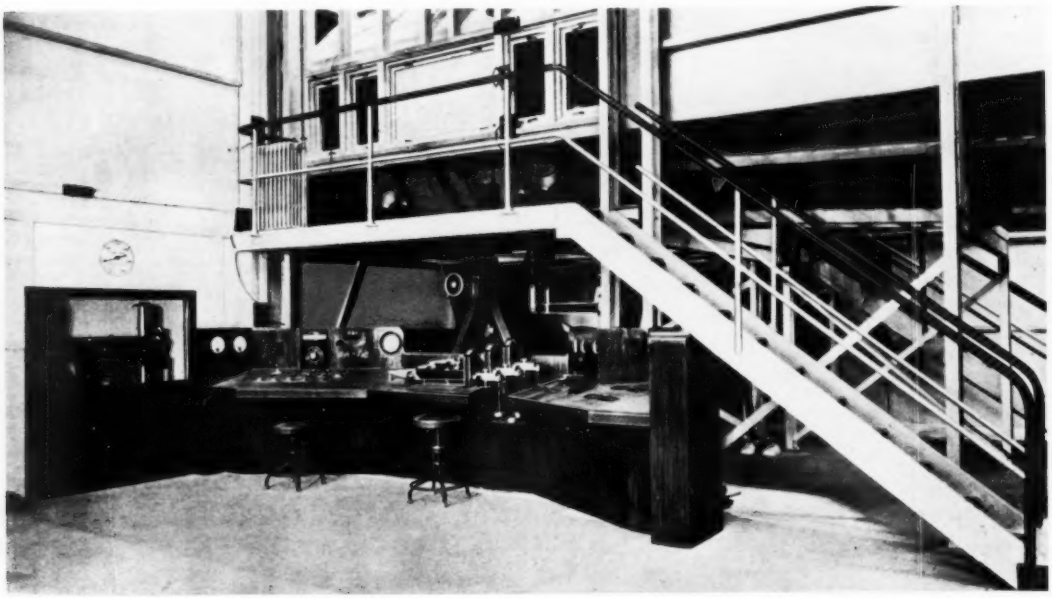

Fig. 3. Control desk and working section of a wind tunnel in Australia. This wind tunnel was constructed during the war.

In this case the main driving motor had a rating of 550 h.p. at 700 r.p.m., and again a synchronous motor was used for driving the D.C. generator. At the time this equipment was supplied the science of electronics had not reached its present advanced stage and the equipment included a

special automatic regulator acting on the field of the generator which gave a high degree of speed constancy. This was, however, inferior to that obtained with the electronic system in operation on the English Electric tunnel at Warton.

Fig. 4 shows a complete fan section built by The English Electric Company during the war for a small wind tunnel installed in this country.

A high degree of accuracy was specified for the shape of the aerofoil supports which were made in Meehanite and ground to size.

A D.C. motor of 110 h.p. 1,200 r.p.m. was installed in the nacelle for driving the fan and the air supply and cables to the motor were passed through the hollow supports.

A speed variation of 10 to 1 was obtained by bucking and boosting an existing D.C. supply.

German Equipment

A notable feature of the German equipment at Volkenrode was the complete reliance on grid controlled rectifier equipments supplying variable speed D.C. fan or compressor motors for subsonic and supersonic wind tunnels.

Fig. 5 shows one of the motor driven compressor sets installed at Volkenrode, the total two-hour rating of the two driving motors being about 13,000 h.p. at 550 r.p.m. The tunnel which this set supplied had two air circuits " a " and " b."

The " a " circuit had a vertical open jet, 1 metre in diameter and a maximum air speed of Mach. number = 0.98, whilst the " b " circuit had a vertical closed working section approximately 94 centimetres square and a maximum air speed of Mach. number = 1.8. Each motor could be coupled to its adjacent compressor for the independent working of each air circuit, but a friction clutch was provided between the two motors so that the total power could be used on either compressor, there being dog clutches also between each motor and compressor.

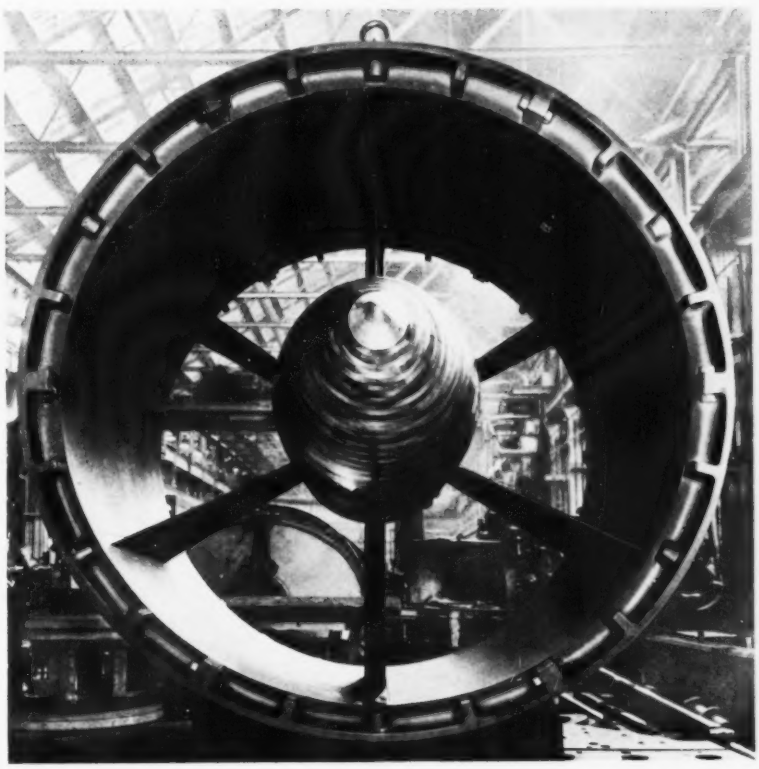

Fig. 4. The complete fan section built by The English Electric Company for a small wind tunnel.

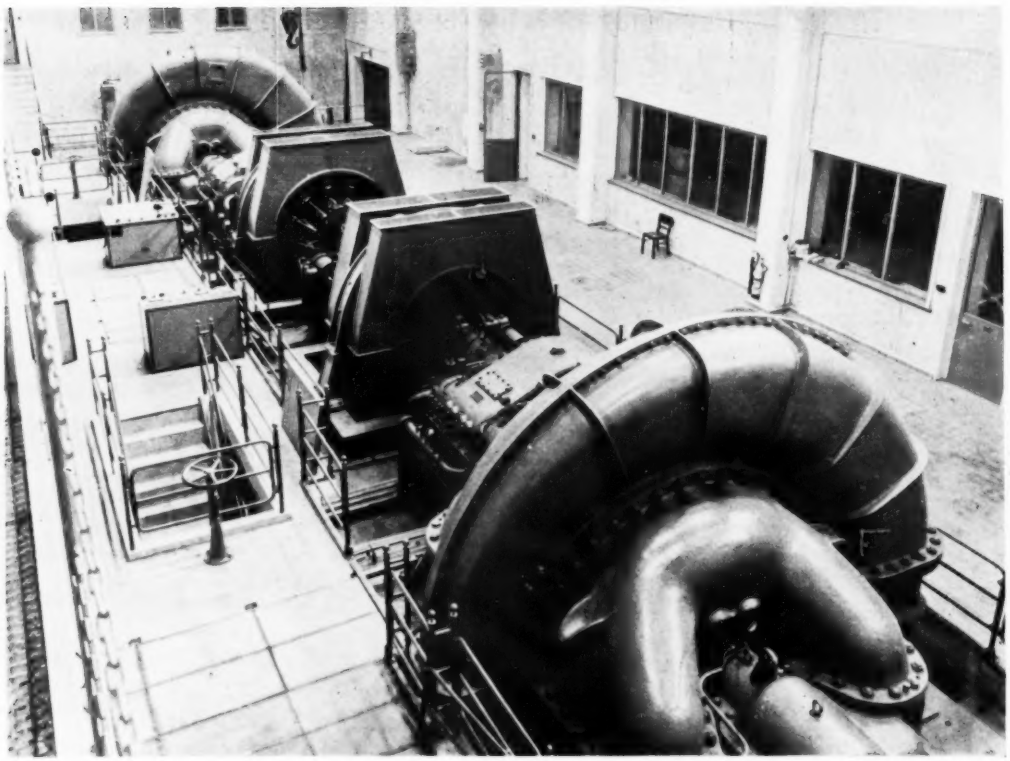

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Fig. 5. A motor driven compressor set installed at Volkenrode, near Brunswick.

The motors were supplied from two grid controlled, water-cooled, steel-tank mercury arc rectifiers, the primary voltage to the rectifier transformers being 50 kV. The main control room was adjacent to the machine hall and is on the right of the photograph in Fig. 5.

The main control board is shown in Fig. 6, and a feature of this and other equipments at Volkenrode was the illuminated diagrams shown on either side of the centre doorway. The various sections of these diagrams were illuminated when the circuits they represented were energised and included such auxiliaries as rectifier cooling water pumps, etc.

The original arrangement for baking out the rectifiers, which was probably necessary if they had not been in use for more than a week, involved the lengthy and cumbersome procedure of changing over the anode connections to low voltage tappings on the transformer, but it was intended to provide means of connecting a 6,000 volt supply to the 50 kV winding of the transformer and closing a shorting link across the D.C. side.

Since a 50 kV supply is not available at the site where this equipment is now installed, The English Electric Company provided a 20,000 kVA transformer 33/50 kV, and also a 5000 kVA transformer 33/6 kV together with the necessary 33 kV and 6 kV switchgear.

The equipment had originally been supplied with a system of automatic speed control but it had proved unsatisfactory and was not in service when the plant was taken over. Development work has been undertaken since in an endeavour to provide a satisfactory electronic system to comply with the high degree of accuracy now required.

One of the difficulties the Germans had to contend with during the war was the very wide supply voltage fluctuations. This may have been unexpected but it is certain that the speed control equipment was totally inadequate according to present British standards.

The working section of one of the large slow speed wind tunnels at Volkenrode is shown in the frontispiece. The diameter of the working section is 8 metres and large enough, as can be seen, for carrying out tests on full-sized aircraft.

In this case the motor was of the nacelle mounted type and Fig. 7 shows the armature of this machine during the course of dismantling operations. It will be noted that the Germans employed the double cell type of commutator construction.

The maximum air speed in this tunnel was equal to a Mach. number of 0.28, the two-hour rating of the motor being about 13,000 h.p. at 250 r.p.m. and again grid controlled steel-tank, water-cooled rectifiers were employed.

Whilst, therefore, the Germans put their faith almost completely in the use of D.C. motors with rectifiers, and the British, generally speaking, concentrated on Ward Leonard equipments, the Americans, because of the large size of their installations, not unnaturally tended to adopt variable speed A.C. drives, as clearly the size of the drive has a definite bearing on the type of electrical equipment which can be employed.

In America therefore one finds large slip-ring induction motors where only a small speed variation is required, one such equipment employing two 25,000 h.p. motors in tandem with ganged liquid speed controllers.

Large synchronous motors have also been used in conjunction with eddy current slip couplings. For very large powers, where high efficiency at partial loads, high power factor and low starting load are necessary, the Americans developed a modification to the Kramer system.

In this scheme the main driving motor is a wound rotor induction motor, the stator being connected in the usual way through a circuit-breaker to the A.C. supply. The rotor, however, is connected to a 3-phase synchronous machine, which is coupled mechanically to a D.C. machine to form a variable speed motor generator set, the speed of which corresponds to the slip frequency of the main driving motor.

The D.C. machine of the variable speed set is connected to a fixed speed motor generator set, the A.C. machine of which is connected to the supply mains. The starting sequence is as follows :

Start the fixed speed motor generator set from the A.C. mains, and when this is up to speed, the variable speed motor generator set is run up under Ward Leonard control from the first set.

The A.C. machine of the second set thus supplies current to the rotor of the main A.C. motor. Its speed is increased until the frequency and voltage induced in the stator of the main motor correspond to the supply voltage and frequency.

The main circuit-breaker is then closed but no current flows until the speed of the second motor generator set is reduced to introduce a difference in frequency between stator and rotor. Rotation of the main motor then occurs at a speed determined by this difference in frequency.

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Fig. 6. Main control board for equipment shown in Fig. 5.

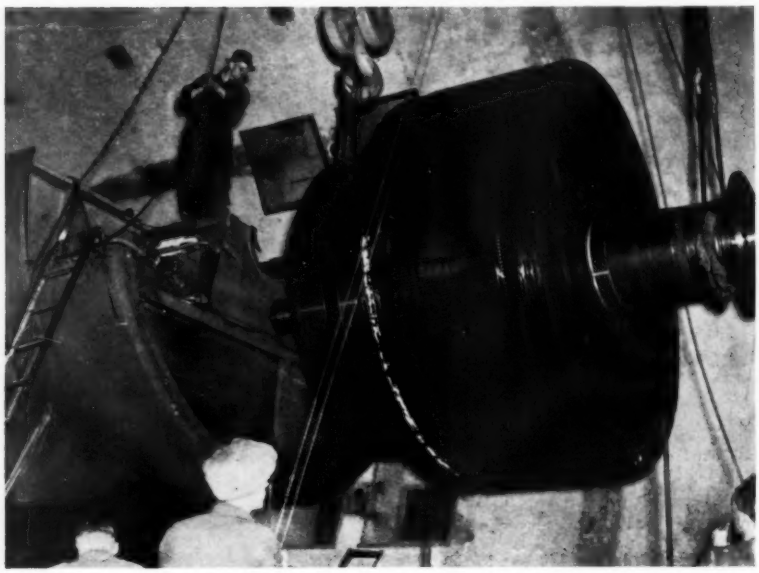

Fig. 7. Dismantling the armature of a nacelle mounted fan motor at Volkenrode. The motor is that of the wind tunnel shown in the frontispiece.

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Speed control in this manner is available up to 10 to 1 and large units of up to 40,000 h.p. have been built.

Another type of composite drive used in America employs a large wound rotor induction motor coupled to a smaller D.C. motor which is operated by Ward Leonard control. The size of the D.C. motor can be such that with the normal fan load characteristic of the horse-power varying as the cube of speed, it can be used alone up to about half speed, above which the A.C. motor is switched in.

The D.C. motor is also used to obtain fine speed control and the scheme could be extended to employ a large synchronous motor in tandem with the D.C. machine, speed variation being obtained from variable speed prime movers driving variable frequency alternators connected to the synchronous motor.

A very large electrically driven wind tunnel taking a supply from the mains is not a very desirable load from the point of view of the power supply authority because of the poor load factor, and it may be necessary to impose limitations on starting current, working hours and rate of change of load.

The availability of a supply of sufficient power has been in some cases a determining factor in the siting of new installations and it must be remembered that with large high density or variable density tunnels, many thousands of horse-power are required by the auxiliary compressors and exhausters.

Tunnels requiring a power of the order of 100,000 h.p. for the main drive, clearly are a case for the consideration of variable speed prime movers either with or without an electrical link. An uncompleted German tunnel discovered in the Munich area is an interesting example of such a drive.

This was designed to employ two 50,000 h.p. Pelton Wheel water turbines driving 15 metre variable pitch fans at a maximum speed of 220 r.p.m.

The tunnel was expected to obtain a Mach. number of 0.85 and the designed accuracy of speed governing was 0.5 per cent. from 40 per cent. of full load speed to full load speed.

The comparison of such an installation with the Wright brothers elementary wind tunnel of nearly 50 years ago is a measure of the progress made in air transport during that period.

The author is indebted to the Chief Scientist, Ministry of Supply, and the Chief Engineer, Ministry of Works, for permission to publish the photographs and description of the German installations.

"English Electric" Equipment in the Wide Hot Strip Mill of John Summers & Sons Ltd., Shotton, Nr. Chester

By G. R. WILSON, B.Sc. A.M.I.E.E., Chief Engineer, Metal Industries Division.

THE NAME OF SUMMERS is well known in the British Steel Industry, dating back to 1860, when Mr. John Summers started a small works at Stalybridge.

The Summers family and the present Company have always tried to keep their Works up to date and as efficient as possible. When about 1938 it became evident that a continuous mill was necessary for the proper production of wide strip and sheet in the desired large tonnages, Messrs. John Summers & Sons, Ltd., embarked on the installation of such a plant.

The English Electric Company obtained the contract for all the main electrical plant associated with this hot strip mill, and it is with the permission of Messrs. John Summers & Sons, Ltd., that we publish the following description. Although this mill was commissioned early in the 1939-45 war, details could not then be published, and even though some time has elapsed since 1945 interest in the mill is still high because it is one of only two in operation in the British Steel Industry (the other also having much " English Electric " main drive equipment). Moreover, the recently modernised " English Electric " flying shear drive has made the mill one of the best in the world for accuracy of heavy sheet size, when sheared at the mill.

The Mill and Its Drives

Before describing the electrical equipment driving the hot strip mill, it is perhaps just as well to review briefly the production stages involved. A slabbing mill elsewhere in the plant breaks the steel ingots down to slabs of the order of 40 in. wide, 5 in thick and 15 ft long, which are then charged as required into the three continuous re-heating furnaces each with a capacity of 60 tons per hour, the hot slabs being then discharged on to a live roller table feeding the first stand of the hot mill. In the mill each slab is passed through successive mill stands, to emerge as a long ribbon of red hot strip which can be coiled or cut into sheets.

A mill of this type requires a considerable amount of space. The mill occupies a length of 1,200 ft in a 150 ft wide building, and the motor room is 420 ft long by 62 ft wide.

The slab first passes through a roughing scale breaker with vertical rolls and driven by two 300 h.p. motors, where the loosened scale is removed by hydraulic sprays, then through three roughing stands which are spaced sufficiently far apart that the piece is in only one stand at a time. Consequently these three stands can be driven by single-speed continuous running motors.

The first roughing stand effects a considerable reduction in thickness of the slab and spreads the slab width if need be. Rolling loads of up to 10,000-12,000 h.p. are imposed on the drive but only for a very short time. To reduce the size of the driving motor, a flywheel is included which, in conjunction with an automatic slip regulator, is able to reduce the motor rating to one of 2,500 h.p. The class LS motor and the flywheel both run at 150 r.p.m. The flywheel has a contained energy of 37,500 h.p. secs.

The two remaining roughing stands, termed " universal " stands, are also driven by 2,500 h.p. motors, one apiece, but in these cases the motors are 375 r.p.m. synchronous units of class GG and with their own direct coupled exciters. Each of these stands has a pair of vertical rolls driven by a 150 h.p. motor. As the strip is subsequently too thin for proper edge-rolling, the edging here is the

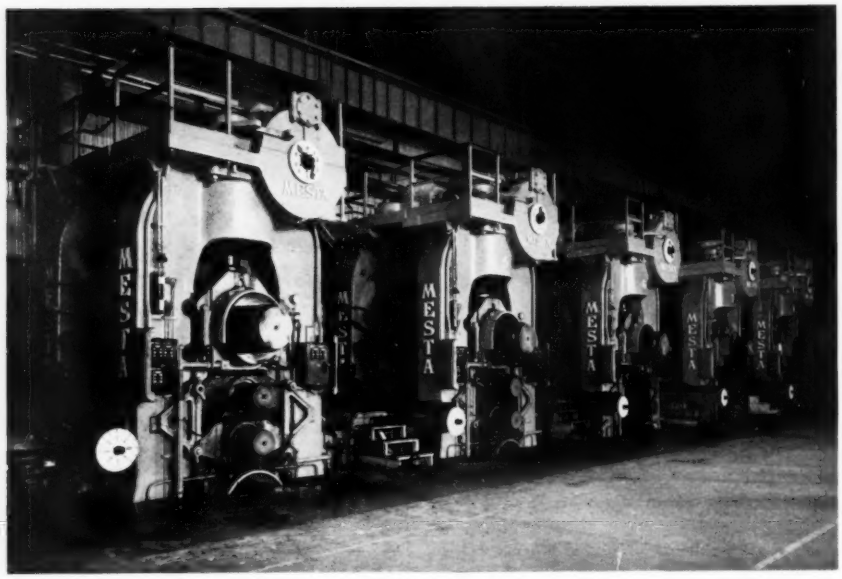

Fig. 1. A general view of the five finishing stands.

last opportunity there is for shaping the strip edges and for finally determining the strip width.

The piece which is now ½ in. to ¾ in. thick is then delivered by the roller tables to a delay table extending 121 ft between the last roughing stand and the finishing scale breaker. The delay table is fitted with drives enabling the strip to be moved to and fro under the action of air cooling to ensure the correct temperature all over the strip before the latter enters the finishing passes.

The finishing train (Fig. 1) has its five 4-high stands closely spaced and driven by individual large variable-speed D.C. motors. These stands and the preceding 2-high scale breaker all act together on the strip, which emerges with a finished thickness in the range .05 in. to about .25 in. Strip widths are 20 to 54 in.

The last finishing stand is followed by the flying shear, where the strip is cut to definite lengths or merely has the front and tail squared. After the shear comes the 400 ft long run-out table with the hot up-coiler almost at the end for coiling the un-sheared strip. Right at the end is the piler for the sheared sheets.

Particulars of all these stands, both roughing and finishing, which have " English Electric " drives, are given in the accompanying table :—

Mill Stand.	Type of Stand.	Work-roll Dia. ins.	Gear Ratio.	Strip Speed Ft./Min.	Motor h.p.	Motor r.p.m.	Type of Motor.
Roughing Stands—							
Vertical Scalebreaker ..					2 × 300	500	Induction.
Spreader Stand	4-high	38	7.84/1	165 mean	2,500	150	Ind. with flywheel.
Universal No. 1	,,	22	7.8/1	277	2,500	375	Synchronous.
Universal No. 2	,,	22	5.46/1	396	2,500	375	Synchronous.
Finishing Stands—							
F.4	4-high	22	5.0/1	230/460	3,000	200/400	D.C.
F.5	,,	22	3.03/1	380/760	3,000	200/400	D.C.
F.6	,,	22	2.12/1	540/1,080	3,000	200/400	D.C.
F.7	,,	22	1.72/1	670/1,340	3,000	200/400	D.C.
F.8	,,	22	1.315/1	770/1,540	2,000	175/350	D.C.

Fig. 2. The 2,500 h.p., 150 r.p.m. drive for the first roughing stand (spreader mill) showing the slip-ring motor, flywheel and slip-regulator.

The roughing stand drives are shown in Fig. 2, while the finishing stand drives are in Fig. 3. These latter stands are at 18 ft centres.

During the time that a strip is in the finishing train stands, the latter are in effect connected together by the piece, and as the ratios of the peripheral speeds of the mill rolls obviously depend on the draft (or thickness reduction) being made in the stands, it is necessary to have closely matched variable speed motors with a very fine degree of speed setting. This necessitates the use of specially strengthened and fully compensated

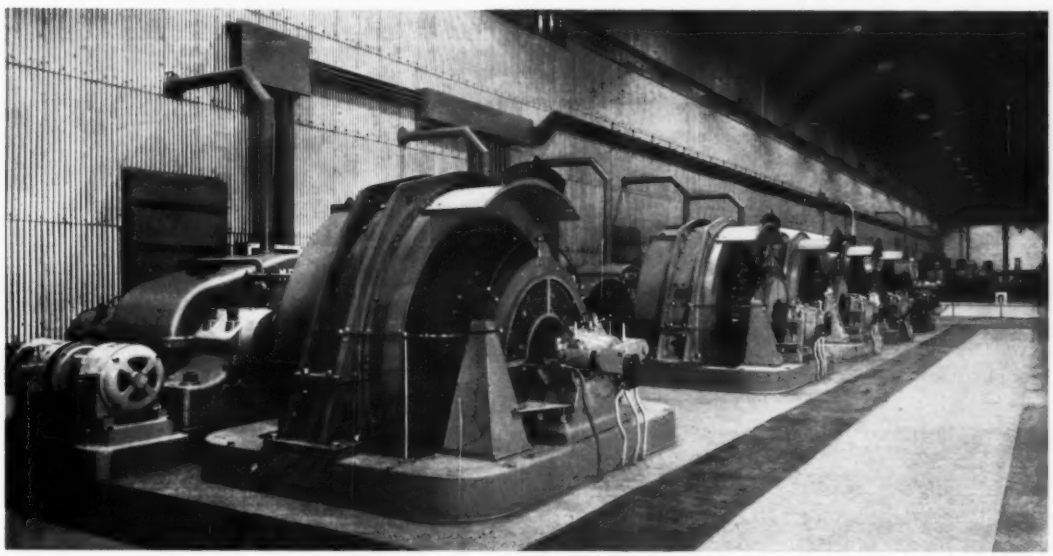

Fig. 3. The four 3,000 h.p. and one 2,000 h.p. D.C. motors driving the five finishing stands.

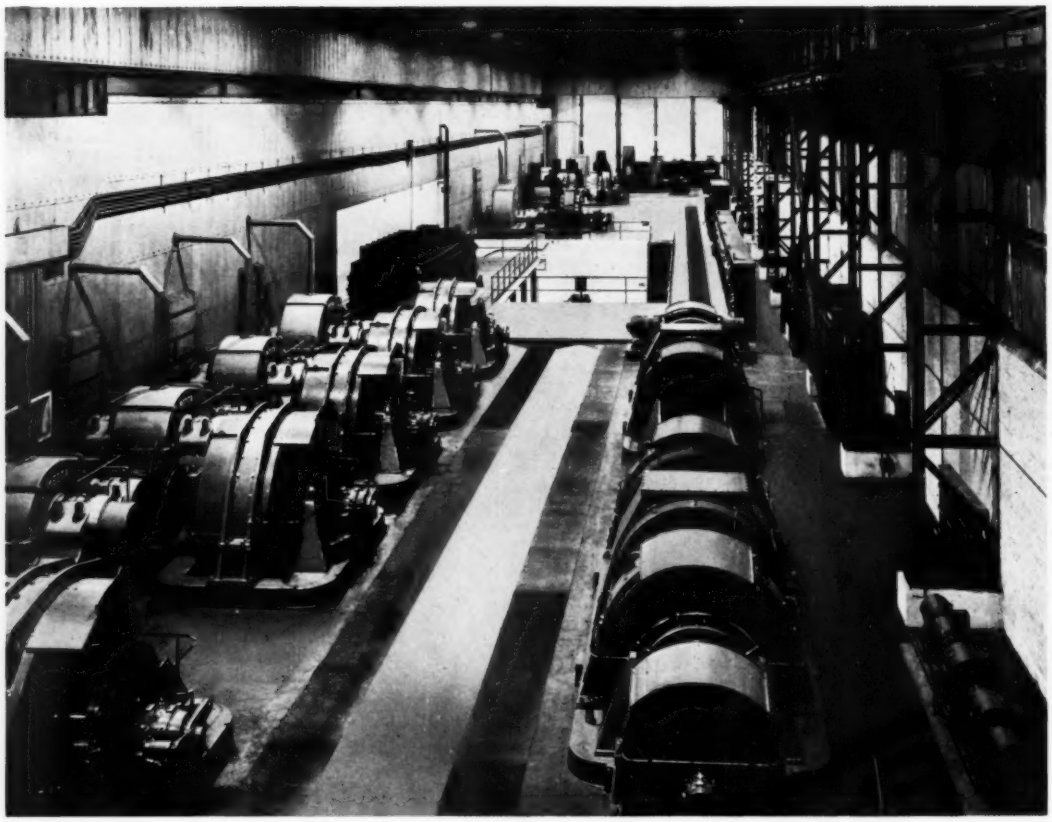

Fig. 4. A general view of the 420 ft long motor room, with the three roughing mill drives in the background, and the five finishing mill drives and their M.G. sets in the foreground.

direct-current motors with a small drop in speed between no-load and full-load.

All the motors of the finishing train are fed from common motor-generator sets so that by simple generator field control the whole mill can have its speed varied as desired, and can be brought up to the correct rolling speed with substantially the right ratios between stand speeds.

It will be noted from the table that the gear ratios are different on the finishing stands, due to the increasing strip speeds as the section is reduced, while the designed motor speeds are equal or similar to one another. In order to secure individual motor speed control for variation in drafting, and to control the strip between stands (to prevent undue looping or tension), each motor is provided with a field-weakening speed range. The coarse control of speed for general setting-up to suit any particular rolling schedule is obtained by motor-driven rheostats operated from control switches at the operator's control pulpit, while fine regulation for loop control is carried out by pulpit-mounted lever-operated vernier rheostats.

The Motor Room

As already mentioned, the motor room is of considerable size, a view from the finishing end being given in Fig. 4. The motors drive via the gears through the wall to the mill stands, while the motor-generator sets are placed longitudinally in

the room.

The two main motor-generator sets are illustrated in Fig. 4. Each has a 7,900 h.p., 6,600 volt, 600 r.p.m. synchronous motor which drives two 2,500 kW, 600 volt generators, making the total available D.C. supply 10,000 kW. These four generators are paralleled on to a common busbar system to supply the finishing motors, but one of the generators is also arranged with changeover and special excitation circuits so that it can function as a 230 volt generator for D.C. shop supplies and so act as a standby to other M.G. sets. Attached to each of the two main M.G. sets is a generator, one of which feeds the flying shear drive motors, the other being a standby.

All these main D.C. machines, both motors and generators, are of the Company's well-known "CS" class which is used always for heavy-duty applications of this nature.

The main connections between the generators, busbars and motors are taken through two single-pole, electrically operated circuit-breakers for each machine, and in view of the concentration of D.C. power which might result in the event of short circuits, the busbars and the poles of the breakers, which are of a special heavy duty type, are spaced in two lines on opposite sides of the basement switchroom, as shown in Fig. 5. It will be observed that the busbars are spaced as widely apart as practicable, close to the wall on each side, and that the connections are well clamped and braced. The generator sets are above at one side of this basement, and the motors above at the other.

Control of the circuit-breakers is basically from a control board in the motor room, as shown in Fig. 4 and Fig. 6. Generator breakers are entirely controlled from this point, but motor breakers are

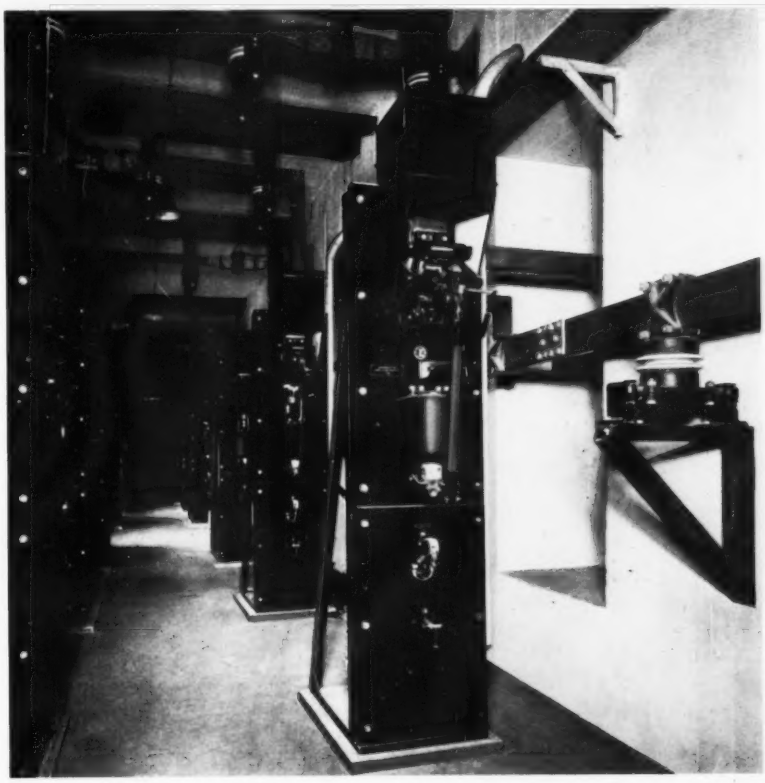

Fig. 5. The basement switch-room for the finishing mill motors and M.G. sets.

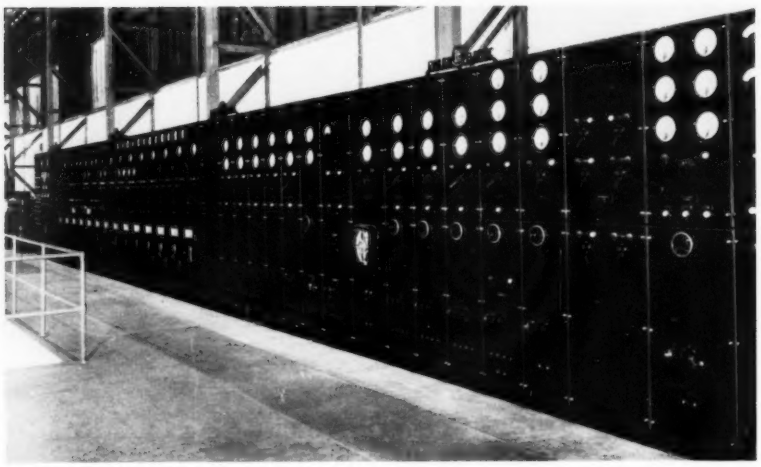

Fig. 6. The central set-up control board for the whole of the mill drives, their ancillaries and certain other gear.

only " preset " so that the mill operators can have the final control according to requirements. This control board also contains the motor field switches and numerous other devices needed in the starting-up and ordinary control and supervision of the whole equipment.

This board is of the dead-fronted type. Towards the right will be seen the automatic voltage regulator which maintains, via the generator exciter, a constant voltage on the busbars at any working value set by the operators and even though the load current drawn by the finishing motors varies between almost zero and 24,000 amperes. When the attendant has closed the necessary circuits from this board, the mill operators are then allowed to close and trip the motor breakers, raise and lower the voltage of the system between zero and the maximum, and vary the speed of each motor in accordance with the rolling programmes.

The mill pulpits are two in number, one for the finishing train referred to above, while the second is located near the roughing stands. The finishing pulpit also provides control of the looper rolls and the flying shear.

Between each finishing stand is located a looper roller with a D.C. motor operated as a torque motor, and fed from a special small motor-generator set. The looper rolls are raised automatically by the passage of the strip through the next following stand, or they can be raised and lowered manually by control switches on the pulpit.

Flying shears are always of special interest in view of their arduous duties, and in the present equipment the electrical shear control system was specially developed by " English Electric " to meet the particular requirements. In view of the recent modernisation of this drive to cover still more accurate requirements and to take advantage of control system developments over the past ten years or so, it is proposed not to give a description of either the original or the new systems but to reserve this for the next issue of the journal.

Ventilation System

The ventilation of the motor room is a very important auxiliary service, since it will no doubt be realised that the total h.p. rating of all the main machines in this room exceeds 55,000, and as most of these machines operate on overload while rolling and well up to their ratings from the heating aspect, the losses of the machines would soon make the temperature in the room unbearable without adequate ventilation plant. The possible heat dissipation requires a flow of about 200,000 cu. ft. of air per minute to keep the motor room temperature to a reasonable figure and if all this air were continuously introduced from outside

there would be, even with the best filters available, a continuous addition of suspended dirt, some of which would inevitably be deposited on the machines and control gear. The ventilation system adopted here re-circulates the bulk of the air through air/water coolers. The pit in the centre of the motor room contains not only the large squirrel cage motor-driven high pressure descaling pumps for the mill, but also two of the fans which blow air along the basement corridors and then up through the machines and into the motor room again. At the finishing mill end of the motor room there is a second pit for air re-circulation, with two more fans. A dry-type filter in the air-path of one of these fans reduces circulation of brush-dust. The motor room is meantime kept under a slight air pressure by introducing filtered air from outside so that mill dirt is excluded as far as possible.

" English Electric " Switchgear

The English Electric Company also supplied the 6.6 kV main switchgear and the starting reactors for the four main synchronous motors (two on the roughing stands and two on the M.G. sets). A 17-panel type OLE switchboard feeds these motors, various general purpose D.C. generator sets, and other services such as power transformers, while also acting as a central distributing board.

Associated with it is a 14-panel type OLD cubicle switchboard, mainly containing the switches required to start the several synchronous motors including those on auxiliary and other M.G. sets. There are only two starting reactors for all these motors, the system being perhaps a little unusual in that isolators determine which reactor can be connected to a reactor bus. To start a motor, the latter is connected to the reactor bus which is in turn connected to the supply. When the motor no longer needs the reactor, the motor terminals are connected directly to the supply and the reactor bus freed for use with another motor as required. Although this system requires one or two more breakers than the simpler system with a reactor for each motor, the total number of short-time-rated reactors is reduced and it is made impossible to start more than one motor at a time. Fig. 7 shows part of both these 6.6 kV switchboards.

Operation

With about ten years' operating experience available with this equipment, it seems worthwhile to record briefly a few notes which may be of general interest.

The mill normally rolls mild steel, the bulk of which goes to the automobile industry while some is made into corrugated sheets. It has also rolled

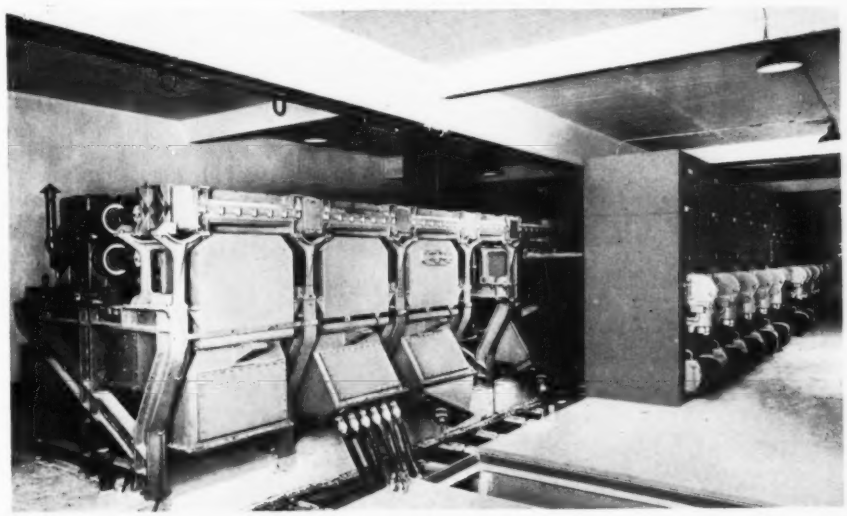

Fig. 7. The rear of part of the 17-panel type OLE 6.6 kV metal-clad board and also the 14-panel type OLD 6.6 kV cubicle type switchboard.

stainless and silicon steel. For mild steel production the electrical consumption averages 60 kWh/ton covering both the main and the auxiliary drives. The average working week amounts to 125 hours.

The maximum number of tons rolled in an 8-hour shift is 1,050, and in a year 470,000 tons. Consequently, around 4,250,000 tons of steel have been produced so far, and the mill has operated continuously during this time without major interruption.

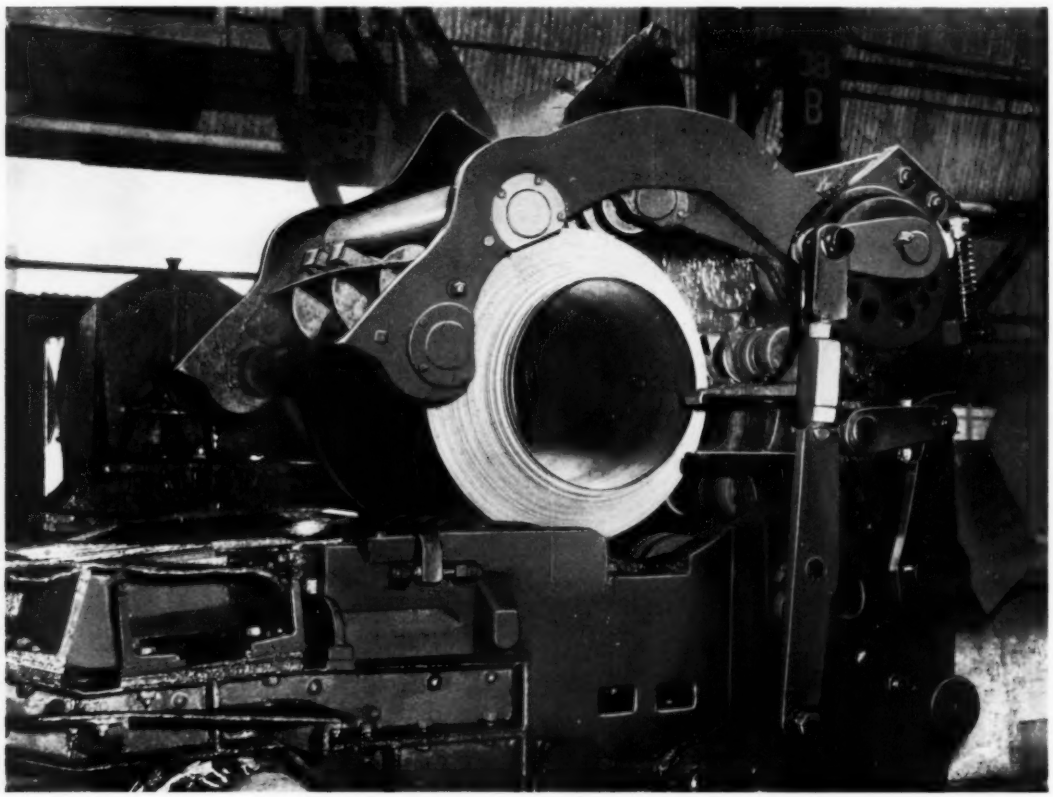

Fig. 8. The strip coiler at the end of a coiling operation.

Statistical Methods Applied to Electrical Insulation

By E. JONES, B.Sc.(Eng.), M.I.E.E., A.M.I.Mech.E., Assoc.A.I.E.E.,
Chief Insulation Engineer.

IT IS A well-known fact that insulation in its many forms is subject to considerable variation in its properties. Statistical methods have been found invaluable for the assessment of insulation quality and for the prediction of insulation performance.

This article is intended to give some brief examples of the application of statistical methods. In some cases, particularly the section dealing with high-voltage stator coils, the number of specimens available for test is of necessity small. It would be advisable to make some allowance for this, but in order to avoid undue complication these allowances are not introduced to any appreciable extent in this article.

For a good practical treatise on statistical methods, British Standard Specification No. 600 should be referred to.

All values of voltage given in this article are R.M.S. values.

Insulating Materials—Magnet Wires

Magnet wires are considered here as materials as they are, in effect, basic raw materials of manufacture.

The assessment of the insulation quality of, for example, enamelled wire, cannot be adequately expressed by determining the breakdown voltage of a few specimens of twisted pairs as the individual values of breakdown voltage of any given quantity of insulated wire are spread over a fairly wide range.

If several hundred breakdown tests are taken on a particular type of wire, and if the results are plotted in the form of a distribution curve, it will be found that the distribution curve of the results is approximately Gaussian in shape, the equation of the curve approximating to :—

$$y = \frac{1}{\delta \sqrt{2\pi}} e^{\frac{-(x-\overline{X})^2}{2\delta^2}}$$

where δ is the Standard Deviation
$\overline{X}$ is the Mean
x is the individual reading (test value).

The curve marked " Wire A " in Fig. 1 is a distribution curve for a particular enamelled wire of bare diameter 0.048 in. It will be seen that the curve has a peak between 4.8 and 5.0kV so that the mean value may be taken as being 4.9kV.

Tests on another wire of different manufacture gave the distribution curve marked " Wire B " in Fig. 1. This has a peak at between 4.4 and 4.6kV, so that the mean value may be taken as being 4.5kV.

If the two wires, A and B, were compared on the basis of the mean breakdown values, it would naturally be concluded that Wire A was superior to Wire B. Further examination of the distribution curves, however, reveals that the individual test values obtained with Wire A are spread out much more than is the case with Wire B.

From this we may conclude that Wire B is a decidedly more consistent material than Wire A and there is much less likelihood of low values of breakdown voltage with Wire B than Wire A. It is apparent that Wire B is the better material to use.

In order to avoid the drawing of distribution curves which require a large number of results to give sufficient points to draw an accurate curve, it is more convenient to use other methods.

The range (i.e., maximum value minus minimum value) of the breakdown values is of some use

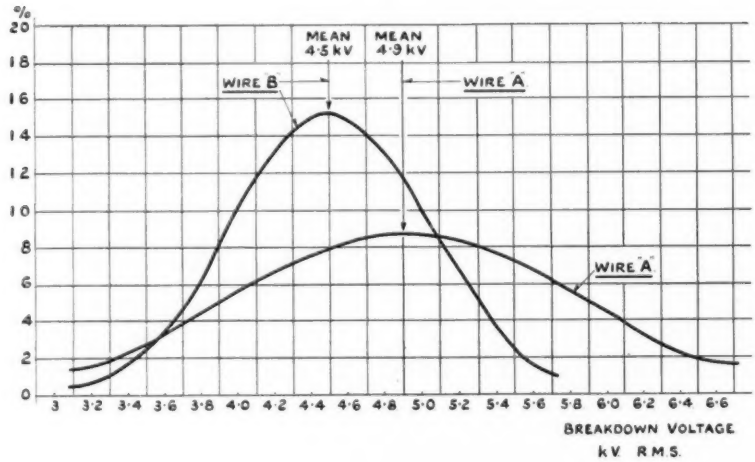

Fig. 1. Normal distribution curves for enamelled wires.

in assessing the spread of the results but the use of the range is essentially unsound as abnormally low (or high) values may appear in the results due to assignable causes such as pinholes or thick spots in the enamel. We are not so much concerned with assignable causes as unassignable causes of variation.

The most generally used measure of spread is the standard deviation. This is defined as the square root of the mean of the squares of the deviations, the general formula being :—

Standard deviation (δ) =

$$\sqrt{\frac{(x_1-\overline{X})^2 + (x_2-\overline{X})^2 + \ldots\ldots (x_n-\overline{X})^2}{n}}$$

Where $\overline{X}$ is the Mean of the test results,

x_1, x_2, etc. . . . . x_n are the individual test results

$(x_1-\overline{X})$, $(x_2-\overline{X})$, $(x_n-\overline{X})$ are the deviations

n is the numbers of test values.

It is a characteristic of the Gaussian distribution that :—

68.27 per cent. of the test values will lie between the Mean $\pm$ δ

95.45 per cent. do. the Mean $\pm$ 2 x δ

99.73 per cent. do. the Mean $\pm$ 3 x δ

Considering the results obtained on Wires A and B, we have :—

Wire A.

Mean instantaneous breakdown voltage, 4.9kV.

Standard deviation (δ), 0.93kV.

$\therefore$ 68.27 per cent. of the test values will lie between (4.9—0.93) and (4.9+0.93) kV, i.e., between 3.97 and 5.83kV.

95.45 per cent. of the test values will lie between (4.9—2×0.93) and (4.9+2×0.93) kV, i.e., between 3.04 and 6.76kV.

99.73 per cent. of the test values will lie between (4.9—3×0.93) and (4.9+3×0.93) kV, i.e., between 2.11 and 7.69kV.

Wire B.

Mean instantaneous breakdown voltage 4.5kV.

Standard deviation (δ), 0.5kV.

$\therefore$ 68.27 per cent. of the test values will lie between (4.5—0.5) and (4.5+0.5) kV, i.e., between 4 and 5kV.

95.45 per cent. of the test values will lie between (4.5—2×0.5) and (4.5+2×0.5) kV, i.e. between 3.5 and 5.5kV.

99.73 per cent. of the test values will lie between (4.5—3×0.5) and (4.5+3×0.5) kV, i.e., between 3.0 and 6.0kV.

The superiority of Wire B is apparent from the above in that 99.73 per cent. of the breakdown values lie between 3.0 and 6.0kV as compared with 2.11 and 7.69kV in the case of Wire A.

The ratio $\frac{\text{Standard Deviation}}{\text{Mean}} \times 100$ is known as the coefficient of variation.

For Wire A the coefficient of variation = $\frac{0.93}{4.9} \times 100 = 19$ per cent.

For Wire B the coefficient of variation $= \frac{0.5}{4.5} \times 100 = 11.1$ per cent.

The two wires may thus be compared in a convenient form as follows :—

Wire A.—Mean instantaneous breakdown voltage : 4.9kV.

Coefficient of variation : 19 per cent.

Wire B.—Mean instantaneous breakdown voltage : 4.5kV.

Coefficient of variation : 11.1 per cent.

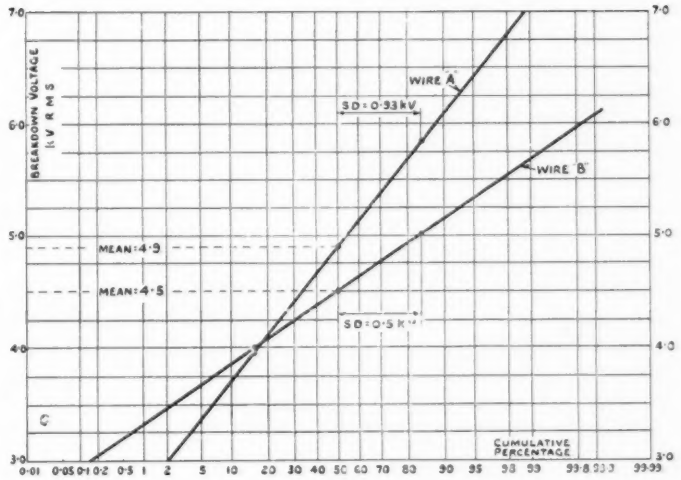

Fig. 2. Breakdown tests on enamelled wire represented on arithmetical probability paper.

Applications of the Results of the Statistical Analysis to Design

Probability Paper

In order to obtain a clearer picture of the electrical breakdown distribution of the enamelled wires dealt with above, use can be made of arithmetical probability paper, as shown in Fig. 2.*

The abscissa of this paper is scaled in cumulative percentage and the ordinate is scaled in breakdown voltage in kilovolts (or any other test function).

The breakdown values are assumed to follow the normal (or Gaussian) distribution curve. This curve is obtained by plotting percentage of breakdowns in a range of breakdown voltage intervals.

If the number of failures which occur below any given voltage and at the given voltage are added up, it is possible to plot a curve of cumulative percentage failures against test voltage. This curve is S-shaped on linear graph paper.

The abscissa scale of arithmetical probability paper is arranged so that the characteristic of cumulative percentage failures against test voltage is a straight line.

A straight line is only obtained if the original distribution is normal (Gaussian).

It should be mentioned that the use of arithmetical probability paper to test for normality can be very misleading as it is not easy to decide whether or not any given plot of points may justifiably be represented by a straight line.

The results obtained with Wires A and B may be set out on the arithmetical probability paper as follows :—

Mark out the calculated mean breakdown value on the 50 per cent. cumulative percentage ordinate.

Mark out a point on the 16 per cent. ordinate at a value of the voltage equal to the mean value minus the standard deviation. Repeat on the 84 per cent. ordinate with the value of mean plus the standard deviation.

These three points will, of course, lie on a straight line such as " A " and " B " in Fig. 2. Line " A " represents Wire A and Line " B " represents Wire B. From the lines it is now easy to read off the probability of failure at any value of the applied voltage. For example, the probability of failure of Wire A at 3.0kV is 2 per cent., i.e., we may expect 2 specimens in 100 to fail when tested at 3.0kV.

Similarly, the probability of failure of Wire B

* This paper may be obtained from Messrs. Wightman Mountain Ltd.

at 3.0kV is only 0.18 per cent., i.e., we may expect only 2 specimens in 1000 to fail when tested at 3.0kV.

In view of the above conclusions, it is apparent that if we are not prepared to admit more than 1 chance of failure in 1000, it would be most unwise to use a voltage higher than 2.0kV between two adjacent wires of type " A " ; a voltage higher than 3.0kV would be unwise in the case of wires of type " B."

Under normal operating conditions, voltages of these orders (2-3kV) are not usual although high inter-turn voltages might arise under highly inductive conditions ; in such cases the instantaneous breakdown voltage level of the wire is the important feature. In order completely to simulate working conditions the tests should be done at the maximum working temperature of the machine so as to allow for the customary fall in dielectric strength with increase of temperature.

Effect on the Test Results of the Area of Dielectric under Test

The results plotted in Fig. 2 are based on individual wire tests on twisted pairs 6 in. long. In practice, the wires may be in contact for much longer lengths than 6 in. and some allowance for this is necessary when assessing the suitability of a given covered wire.

Hill and Schmidt* have dealt with this subject in some detail and they show that the theoretical cumulative probability of breakdown for " k " elemental areas in parallel is related to the cumulative probability of breakdown for an elemental area by the expression—

$$\text{Cum. } P_{BDk} = 1 - (1 - \text{Cum.p})^k \quad \ldots\ldots\ldots (1)$$

where Cum. P_{BDk} is the cumulative probability of breakdown at V volts for k elemental areas in parallel ;

and Cum.p is the cumulative probability of breakdown for one elemental area.

Fig. 3 gives a series of characteristics on arithmetical probability paper showing the effect of testing with specimens having 2, 4, 10, 100 and 1,000 times the area of the elemental area.

Strictly speaking, the above formula (1) gives curves on arithmetical probability paper, as the derivation of the formula is based on the binomial distribution, but straight lines are assumed as they make for greater simplicity in use.

From Fig. 3 it is seen that to maintain a maximum of 1 in 1000 probability of failure (0.10 per cent.), the following inter-conductor voltages should not

* Insulation Breakdown as a Function of Area, L. R. Hill and P. L. Schmidt, A.I.E.E. Proc., 1948, Vol. 67, Section T. 869.

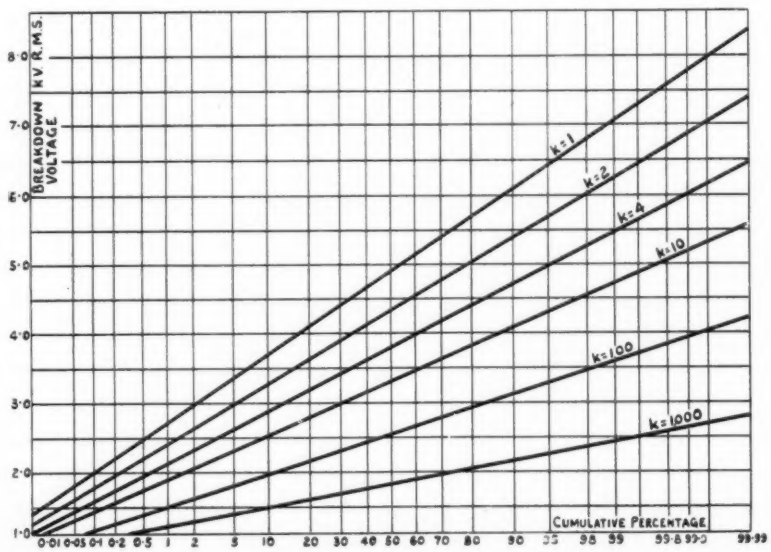

Fig. 3. Breakdown tests on enamelled wire (Wire " A ") represented on arithmetical probability paper, showing effect of area of dielectric under test.

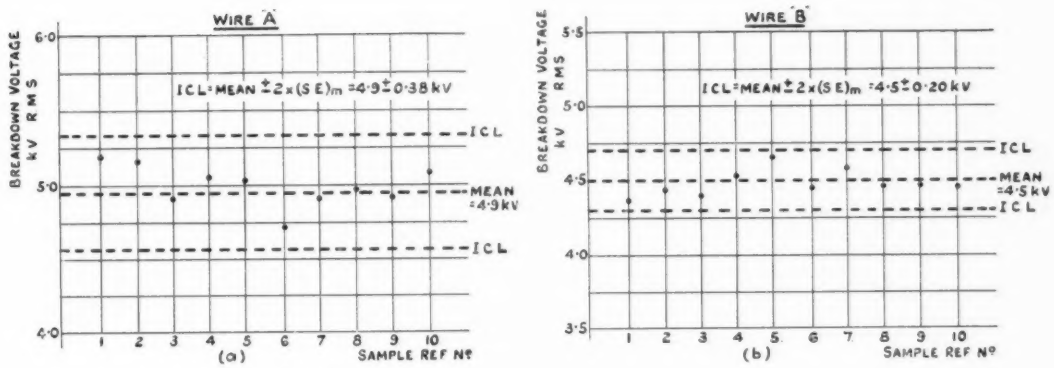

Fig. 4. Typical control charts for mean instantaneous breakdown voltage of enamelled wires.

be exceeded with Wire A :—

k= 1 i.e., 6 in. length of specimen : 2.0kV.
k= 4 i.e., 24 in. length of specimen : 1.6kV.
k= 10 i.e., 60 in. length of specimen : 1.4kV.
k= 100 i.e., 600 in. length of specimen : 1.2kV.
k=1000 i.e., 6000 in. length of specimen : 0.9 kV.

It is apparent from these figures that when considering a particular quality of insulated wire for use in, for example, mush-wound stators, some estimate of length of contact of wires at widely different potentials must be made.

Wires A and B offer an ample margin of safety for low-tension (up to 660 volts) mush windings, but in view of the fact that the long-time dielectric strength is lower than the instantaneous value and in view of the additional fact that the dielectric strength drops with increase of temperature, Wire A would be considered unsuitable if no inter-phase insulation was to be used in the windings as the " 1 in 1000 " level might then well be less than 660 volts.

Control of the Quality of Insulated Wire

The routine testing of incoming consignments of insulated wire must be sufficient to be able to assess the quality of the material but the amount of testing must obviously be kept to the minimum in order to save time.

The standard deviations of Wires A and B are 0.93kV and 0.5kV respectively. These values of standard deviation were calculated from many hundreds of tests so they can be considered as the " Universe " values.

The Standard Error of the mean is given by the expression :—

$$(S.E.)_m = \frac{\delta}{\sqrt{n}} —$$

where n is the number of tests taken.

Let it be assumed that a sample of 4 specimens was tested from both Wire A and Wire B. The values of the $(S.E.)_m$ would be :—

$\frac{0.93}{\sqrt{4}}$ = 0.47kV for Wire A, and

$\frac{0.50}{\sqrt{4}}$ = 0.25kV for Wire B.

It is known that the mean value of the material will not differ from the sample mean ($\bar{x}$) by more than $\pm 2 \times (S.E.)_m$.

i.e., by ± 0.94kV for Wire A, and ±0.5kV for Wire B.

If a sample of 25 specimens was taken from each wire the values of $(S.E.)_m$ would be :—

$\frac{0.93}{\sqrt{25}}$ = 0.19kV for Wire A and

$\frac{0.5}{\sqrt{25}}$ = 0.10kV for Wire B.

Therefore the material mean would now not be likely to differ from the sample mean ($\bar{x}$) by more than :—

± 0.38kV for Wire A, and ± 0.20kV for Wire B.

It is apparent that the samples of 25 give a very much closer estimate of the "Universe" Means ($\bar{\bar{X}}$) than samples of 4, and it is most desirable that we work with samples of at least 25 specimens.

The standard error of the Mean is identical with the standard deviation of the Means ($\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$, etc.). The value of $(S.E.)_m$ thus enables us to set control limits for the sample Means.

The values of $\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$, etc., i.e., the sample Means, are distributed normally about the Universe Mean $\bar{\bar{X}}$ with a standard deviation of $\frac{\delta}{\sqrt{n}}$, hence it is known that 95.5 per cent. of the value $\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$, etc., will lie within the limits $\bar{\bar{X}} \pm 2 \times \frac{\delta}{\sqrt{n}}$.

For Wire A, $\bar{\bar{X}} = 4.9$kV and $\frac{\delta}{\sqrt{n}} = 0.19$kV.

Hence the inner control limits for Wire A are
$4.9\text{kV} \pm 2 \times 0.19\text{kV} = 4.9\text{kV} \pm 0.38\text{kV}$.

Similarly for Wire B, the I.C. limits are
$4.5\text{kV} \pm 0.20\text{kV}$.

It is thus possible to construct control charts such as are shown in Fig. 4 (a and b), which show the Universe Means ($\bar{\bar{X}}$) and the I.C.L.'s. The Mean value x of each sample of 25 specimens may be represented as a dot on the diagram and at least 95.5 per cent. of these dots should lie within the I.C.L.'s.

It is found, in practice, that it is very unusual for any Mean values of instantaneous breakdown voltage to lie below the lower I.C.L. There is, of course, no objection with enamelled wires to values lying above the upper I.C.L., although naturally such high values would justify a closer examination of the other characteristics of the wire (enamel thickness, flexibility, etc.).

It would be reasonable to specify the lower I.C.L. as the minimum acceptable Mean instantaneous breakdown voltage of the wire. The variation of the individual values of breakdown voltage within any sample can be controlled by setting out limits for variation of these individual values.

Suitable control limits may be set at
$\bar{\bar{X}} \pm 2 \times \delta$

For Wire A the limits would be :—
$4.9\text{kV} \pm 2 \times 0.93 = 3.04$ to 6.76kV, say 3.0 to 6.75kV.

For Wire B the limits would be :—
$4.5\text{kV} \pm 2 \times 0.50 = 3.5$ to 5.5kV.

These limits may be set out as in Fig. 5 (a and b). The sample individual results may be set down as dots, and at least 95.5 per cent. of these dots should lie between the inner control limits. Here again, the upper I.C.L. is mainly of academic interest.

Insulating Materials—Slot Insulations

It has been seen how any particular make of enamelled wire may be assessed for use in electrical machines, and it has also been seen how the quality of the material may be checked to maintain the quality.

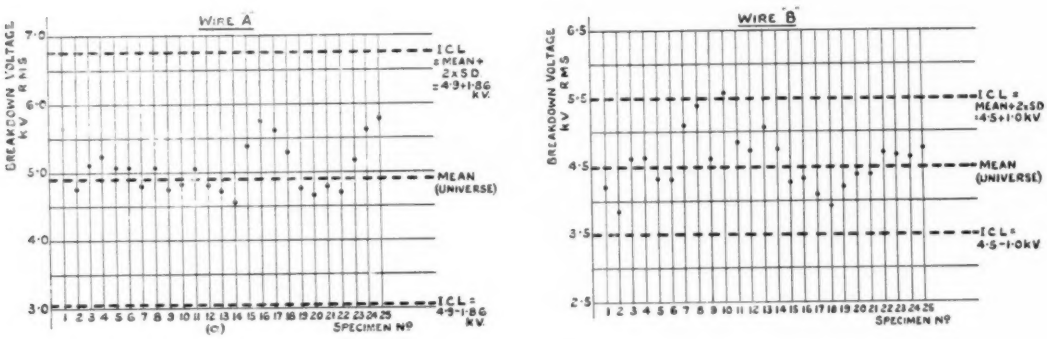
WIRE A
BREAKDOWN VOLTAGE KV RMS
7·0
6·0
5·0
4·0
3·0
I.C.L. = MEAN + 2 x SD = 4·9 + 1·86 KV.
MEAN (UNIVERSE)
I.C.L. = 4·9 - 1·86 KV.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
(c)
SPECIMEN Nº
WIRE B
BREAKDOWN VOLTAGE KV RMS
6·5
5·5
4·5
3·5
2·5
I.C.L. = MEAN + 2 x SD = 4·5 + 1·0 KV.
MEAN (UNIVERSE)
I.C.L. = 4·5 - 1·0 KV.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
SPECIMEN Nº

Fig. 5. Typical control charts for sample tests of instantaneous breakdown voltage of enamelled wire.

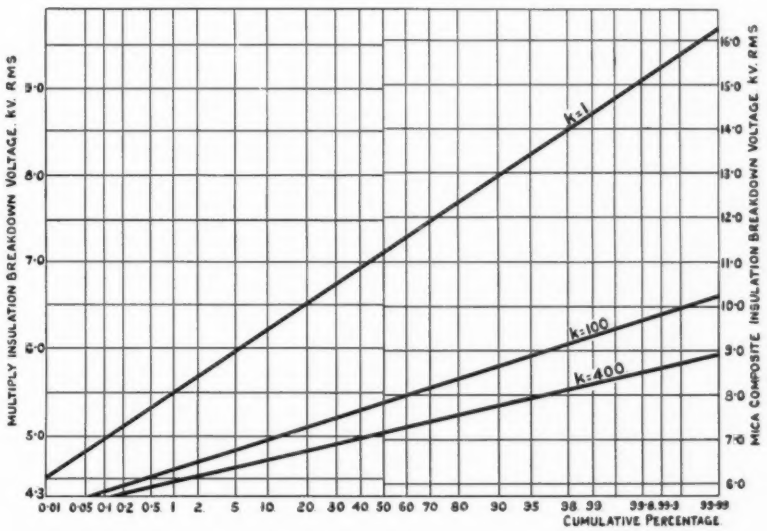

Fig. 6. Breakdown tests on slot insulations showing effect of area of dielectric under test.

The assessment and control of material such as multi-ply or mica composite flexible slot liner materials may be undertaken in a similar fashion.

A certain multi-ply slot insulation was submitted for test and the following results were obtained :—

Mean instantaneous breakdown voltage : 7.1kV.

Standard deviation : 0.7kV.

Coefficient of variation : 9.9 per cent.

If these results be represented on arithmetical probability paper (Fig. 6), it will be seen that for less than 1 in 1000 chance of breakdown, the maximum voltage applied must not be greater than 4.9kV.

The tests were done with electrodes of 3 square inches area.

If this material were being considered for a machine where the total area of liner between winding and earth was, say, 300 sq. in. (i.e., k = 100), the maximum voltage which may be applied so that the chance of failure is less than 1 in 1000 machines may be obtained from Fig. 6. This value is 4.4kV.

It should be noted that the test values given above are instantaneous breakdown values. As the machines under consideration have to withstand a 1-minute test at 2.5kV when hot (after the test run), it is apparent that the tests on the slot liner material should have been 1-minute step-by-step tests at 90°C.

In the case of the above material it was found that if 1-minute step-by-step breakdown values at 90°C were considered, the maximum safe voltage was 2.8kV (for 1 minute at 90°C), so as not to exceed the 1 machine in 1000 chance of failure. As the machine test voltage is 2.5kV it would be preferable to choose a material with a somewhat higher margin of safety.

Tests on an alternative supply of multi-ply insulation gave a Mean 1-minute step-by-step breakdown voltage at 90°C of 13.0kV with a standard deviation of 0.74kV when testing with an electrode area of 3 square inches. Adjusting the results to allow for area (300 square inches) as before, showed that for the chance of failure not to exceed 1 machine in 1000, the 1-minute test voltage must not exceed 10.1kV.

This material offers a large margin of safety over the 1-minute test voltage of 2.5kV, and would be classified as highly satisfactory or perhaps too good for the job (this would depend on economic considerations).

Quality Control of Slot Insulation

For checking the dielectric quality of incoming consignments of slot insulation it is desirable to use a test which is non-destructive. A convenient test is to pass the sheets of material between metal rollers between which a suitable test voltage is

applied. This type of test is equivalent to an "instantaneous" voltage test, hence the test voltage may be chosen from the results of previous instantaneous breakdown voltage tests.

When tested for instantaneous breakdown, a particular type of mica composite slot insulation gave the following results :—

Mean instantaneous B.D. voltage : 11.2kV.

Standard deviation : 1.37kV.

Coeff. of variation : 12.3 per cent.

These tests were taken using an electrode area of 3 square inches. The roller test, however, tests a whole sheet 30" × 40", i.e., 1200 sq. in., so that $k = \frac{1200}{3} = 400$.

Referring to Fig. 6, it is seen that if the voltage between the rollers is 5.5kV, the chances are that not more than 1 sheet in 1000 will fail the test due to unassignable causes. Any failures which occur at this voltage will most probably be due to assignable causes such as a pinhole or a metallic inclusion in the sheet.

The roller-test voltage may therefore be set at 5.5kV and all sheets may be passed through this test.

Insulated Components

(*a*) Armature Coils

It is common practice in the manufacture of wound machines to test the windings, during processing, at voltages higher than the test voltage required by the appropriate British Standards Specification.

The danger with this practice is that if the winding process is subdivided into several stages, such as is the case with traction machines, the shop-test voltages specified for the first stage or so may be unnecessarily high and may result in an unnecessarily high level of failure. Statistical analysis gives a sound method of determining the maximum test voltages which should be applied.

One-minute step-by-step breakdown tests were carried out on the slot portions of 25 armature coils. The electrode length was 2" so that two tests were possible per coil side. One hundred test values were thus obtained.

The results were :—

Mean 1-min. step-by-step B.D. value : 13.3kV.

Standard deviation : 1.3kV.

Coeff. of variation : 10.0 per cent.

(i) Testing of individual coil-sides in a metal trough representing a core length of 10".

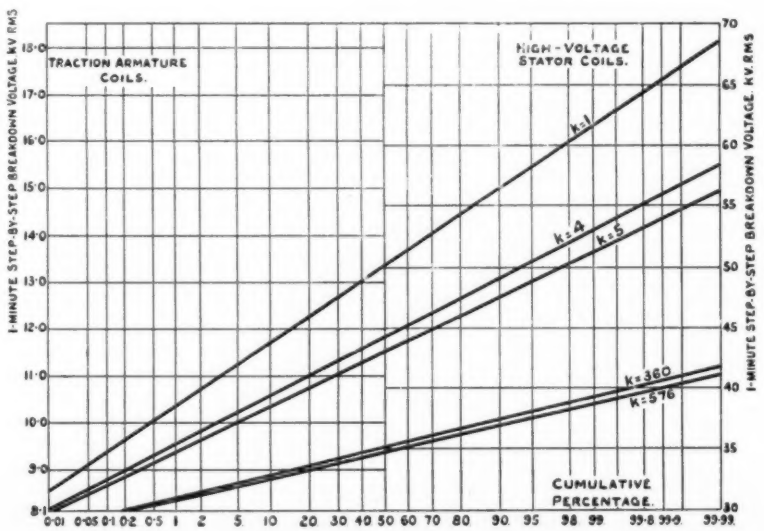
1-MINUTE STEP-BY-STEP BREAKDOWN VOLTAGE KV RMS
TRACTION ARMATURE COILS.
HIGH-VOLTAGE STATOR COILS.
k=1
k=4
k=5
k=360
k=576
CUMULATIVE PERCENTAGE.
0·01 0·05 0·1 0·2 0·5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99·8 99·9 99·99

Fig. 7. Dielectric breakdown tests (1-minute step-by-step) on armature coils and high voltage stator coils.

In this case $k = \frac{10}{2} = 5$

Referring to Fig. 7, it is seen that the 1 in 1000 limit is 8.6kV, hence the test voltage for individual coil sides should never exceed 8.6kV for 1 minute.

(ii) Testing of a wound armature of core length 10″ and having 36 slots.

In this case $k = \frac{720}{2} = 360$

Referring to Fig. 7, it is seen that the 1 in 1000 limit is about 8.0kV, hence the test voltage for the wound armatures should never exceed 8.0kV for 1 minute.

(*b*) High-Voltage Stator Coils

One-minute step-by-step breakdown tests were done on a number of 11kV turbo-alternator stator coils, using electrodes 34″ long on the slot portions. The following results were obtained :—

Mean 1-min. step-by-step B.D. value : 50 kV.

Standard deviation : 5kV.

Coeff. of variation : 10 per cent.

In this case the core length was 136″, i.e., $k = \frac{136}{34} = 4$, say, for the individual coils sides, hence the 1 in 1000 limit for testing individual coils sides is (from Fig. 7) 33.0kV for 1 minute.

Assuming 72 slots in the stator, $k = \frac{72 \times 136 \times 2}{34}$ = 576 for the wound stator, hence the 1 in 1000 limit for testing wound stators is (from Fig. 7) 29kV.

It can be concluded therefore :—

(i) In order that the chances of failure of individual coil sides shall not exceed 1 coil side in 1000 when testing individual coil sides, the test pressure must not exceed 33.0kV.

(ii) In order that the chance of failure of wound stators shall not exceed 1 stator in 1000 when testing complete windings, the test pressure must not exceed 29kV.

Conclusions

The examples quoted in this paper have been intended to illustrate the great value of statistical analysis in the practical assessment of insulation materials and insulated components or machines.

The correlation between predicted behaviour and actual results in practice has been found to be remarkably close even in cases where the numbers of test samples, for setting limits of control, are of necessity small as in the case of stator coils for large generators.

Statistical methods most certainly enable the engineer in many cases to assess and predict with useful accuracy the behaviour of that hitherto rather unpredictable quantity—insulation.

The Protection of Gas Turbine Air Intakes Against Sand and Ice

By C. L. COWDREY, F.R.Ae.S., M.S.A.E., Chief Installation Engineer, D. Napier and Son, Ltd., Experimental Establishment, Luton.

Introduction

IT HAS BEEN apparent for some time that the problem of providing an ice-immune air intake for turbine engines, especially those of the type embodying axial flow compressors, is one to which special attention must be given by the engine and installation designers at the very inception of the engine layout. Tests already carried out in Canada, U.S.A., and in this country, have been somewhat conflicting but it is now clear that severe damage and perhaps complete catastrophe to engines of this sort can arise from the breaking away of comparatively small particles of ice from the surfaces of the air intake.

The problem of providing an ice free intake and of cleaning of the air for desert operating conditions is accentuated by the high specific air mass flow of turbine engines.

Fig. 1 has been prepared to illustrate this point, and is a comparison of the air consumption rates of three types of engine, in lbs. of air per second per lb. thrust at 300 m.p.h. at 20,000 ft.

It is clear from this diagram that the embodiment of fabric in filters of the type developed for piston engines would be impracticable. Consequently, the Napier Company has concentrated on the development of a momentum separating intake, which in addition to providing a high degree of air cleaning will, it is hoped, reduce the moisture content of the aspirated air, and thus reduce or eliminate the danger of ice formation. The following is a summary of the major requirements of the design :—

(*a*) The intake should be capable of removing sufficient moisture from the aspirated air to avoid the danger of ice build-up on the compressor blades or on the duct surfaces just ahead of them.

(*b*) The intake should be automatic in action so that the need for a manual control operated by the pilot is rendered unnecessary.

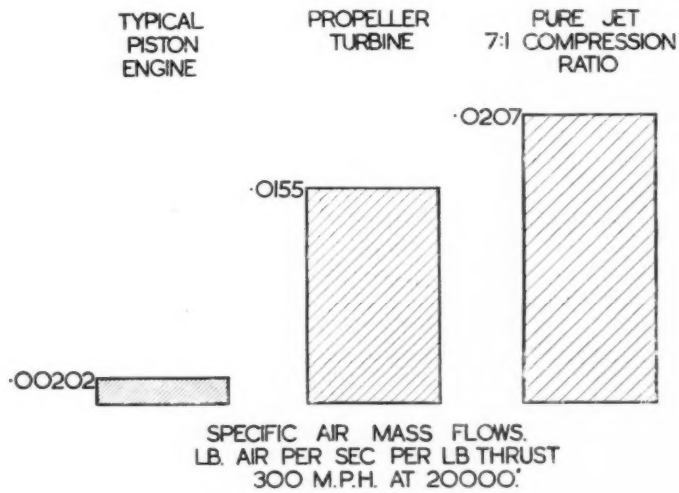

Fig. 1. Comparison of specific air consumption of piston, propeller turbine and pure jet engines.

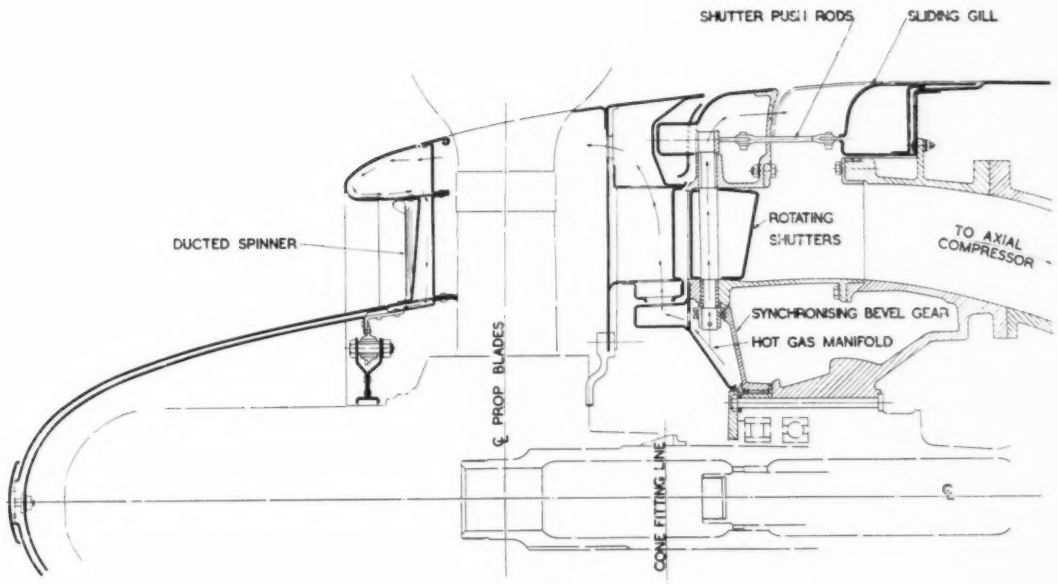

Fig. 2. Naiad air intake with radial shutters and flush slot alternative entry.

(*c*) The pneumatic efficiency should remain high, say, of the order of 70 per cent. to 80 per cent.

Intake for Naiad Engine

It appears that many aircraft and engine designers are working on similar lines and Fig. 2 shows an intake scheme produced by the Napier Company for the Naiad engine. A full ramming intake is provided in the normal way, via a ducted spinner entry. The ramming intake embodies a series of rotatable shutters disposed radially and arranged so that they may be closed by the pilot when icing conditions are imminent. As the shutters close, the flush slot entry in the nacelle cowling is opened by a sliding gill, thus providing an alternative intake to the engine. When flying under icing conditions it is clearly essential to prevent ice forming on the inner surfaces of the spinner, since when clean air conditions return and the ramming intake is reselected, ice may break away from these surfaces and enter the engine. A system of thermal de-icing for the spinner is therefore proposed, and in the illustration hot gas passages have been shown, the gas being fed into the spinner from a fixed manifold in the engine. The shutters themselves are similarly protected. A similar anti-icing scheme for ducted spinners has been proposed by Mr. Elliott and illustrated in the proceedings of the Royal Aeronautical Society's Joint Conference with the Institute of Aeronautical Sciences.

Rig Tests on Momentum Intakes

A considerable programme of test work has been carried out at Luton on rigs embodying the essential features of the intake already illustrated. It was felt that in view of the difficulty of establishing a satisfactory technique for measuring the separating efficiency of these intakes with moisture laden air, the work could best be forwarded by concentrating in the first instance on determining their efficiency as sand separators. Fig. 3 shows the apparatus which Napiers have used, comprising a blower tunnel, delivering air at 240 ft/sec. through a nozzle about 11 in. diameter. This tunnel is

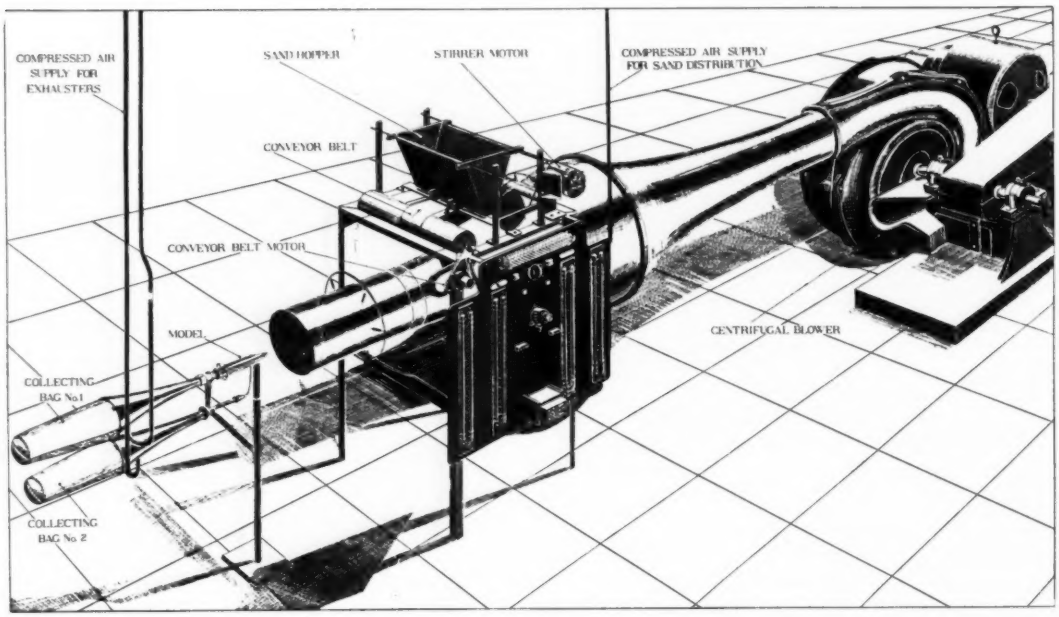

Fig. 3. *Blower tunnel with small model intake.*

fitted with the sand metering device developed by Mr. Bigg at the R.A.E. and comprising a hopper, a variable speed conveyor belt and sand feed injector nozzles. A cloth filter element is provided in the pipe line leading from the model and the aspiration of the engine is simulated by an exhauster fan. The technique of testing is to run the air intake under ramming conditions at fixed entry velocity ratios and at a sand concentration of 30 mgs/cu. ft. for 10 minutes, subsequently weighing the amount of sand caught in the filter bag. A corresponding test is then carried out with the ramming entry closed and the flush entry open. The separating efficiency is then expressed as the ratio of :—

$$\frac{\text{sand eliminated by flush entry.}}{\text{sand absorbed by ramming entry.}}$$

Fig. 4 shows the particle size distribution of the sand mixture adopted by Napiers compared with the R.A.E. Specification.

Results of Tests on Naiad Engine

Rig tests have also been carried out on a section of the Naiad air intake previously illustrated, the method of testing being illustrated in Figs. 5 and 6. In these cases an attempt has been made to eliminate scale effect by testing a two-dimensional representation 4 in. wide of the full scale ducted spinner and flush slot intake. Fan power is sufficient to produce airflow conditions up to 160 m.p.h. and velocity ratios up to ·4. These conditions approach closely those obtaining during the initial climb of a typical aircraft.

Some of the results are shown in Fig. 7, and the tests have taken the form of separating efficiency checks and the determination of entry loss coefficient for the flush entry at various velocity

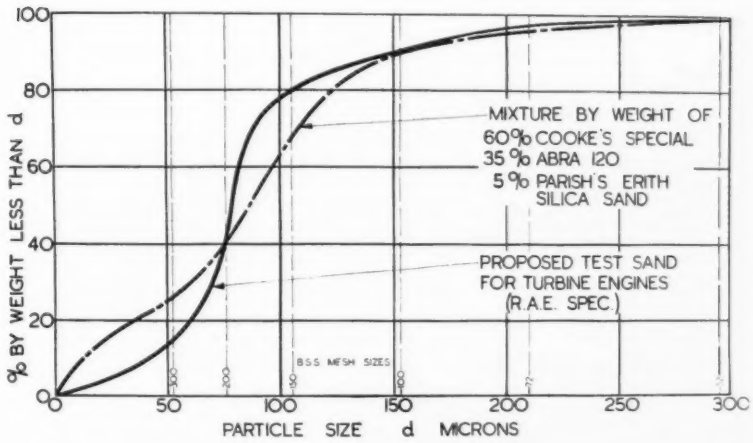

Fig. 4. Sand particle size.

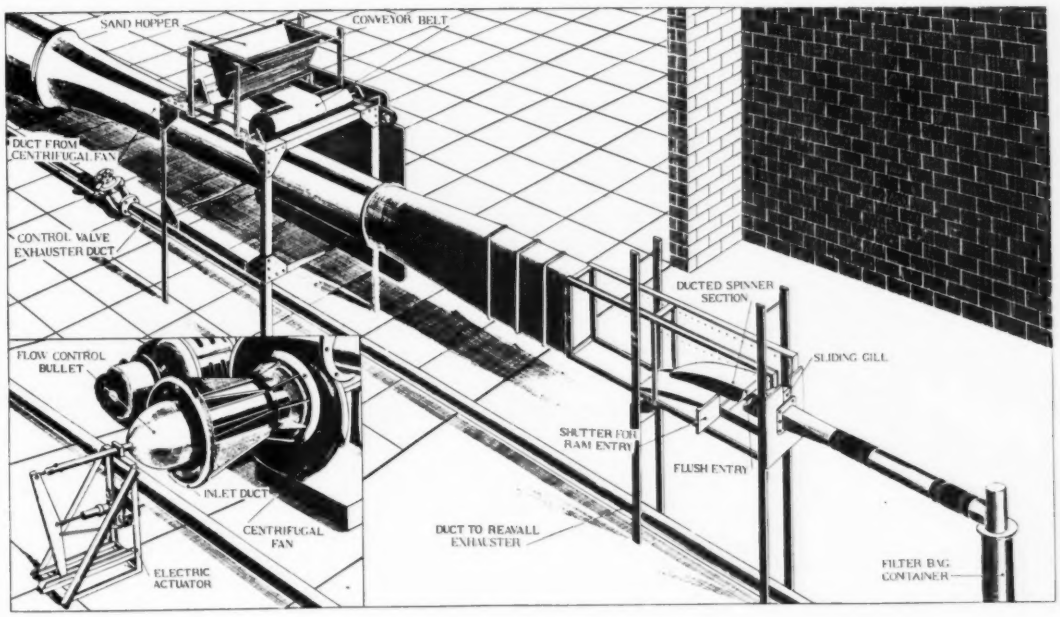

Fig. 5. Blower tunnel with Naiad intake.

ratios and slot widths.

The separating efficiency in all practical cases is about 95 per cent. and is practically independent of the slot width within the limits tested. For example, at an entry velocity ratio of ·4 and the designed slot width of 3 in., separating efficiency is 97 per cent. The disadvantage of this system, however, lies in the high aerodynamic losses incurred in the flush slot entry. Various entry passage shapes are now being tested in an attempt to compromise between low entry losses and high separating efficiency. Taking a typical case, with an entry velocity ratio of ·4, the total head loss up to a station corresponding to the compressor entry at a slot width of 3 in. is some 2·6 of the freestream dynamic head, a loss which is too high

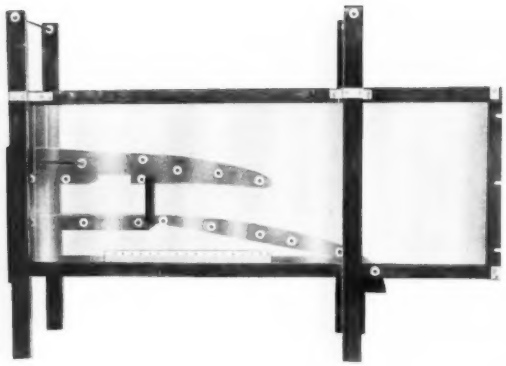

Fig. 6. Section of Naiad intake.

to be tolerable in the actual installation. In physical terms this is equal to 63 in. W.G. at 300 m.p.h. at 20,000 ft. and represents a loss of 30 per cent. of the overall compressor pressure ratio referred to a normal intake.

The Napier Company feel, however, that if this pressure loss can be reduced to, say, ·5 q_0 whilst maintaining a cleaning efficiency of over 95 per cent., the loss in engine power when using the flush entry might be acceptable for transient conditions, and it is anticipated that the redesign of the entry will achieve this result.

Use of Wax Particles to Simulate Water Droplets

Having devised a suitable technique for the determination of separating efficiency under desert conditions, Napiers felt it desirable to adapt its present test rigs to determine the corresponding efficiency of the separation of moisture droplets, with the minimum of change of test technique. It was first suggested by Napiers that the problem could be approached by adopting spherical particles of an inorganic material such as a plastic with a specific gravity close to 1. Enquiries were therefore made of I.C.I. for a suitable material for this purpose. Methyl methacrylate resin (perspex) is available from the I.C.I. under the trade-name "Kallodoc." This material is supplied to the dental industry in the form of spherical particles of size ranging from 10μ to 180μ and has a specific gravity of 1·2. It is, however, expensive—the cost being forty shillings per lb.—and is in short supply. The R.A.E. have suggested an alternative, namely, the use of Carnauba (Brazil) Wax, which has a specific gravity of ·995, and a melting point of 80° C. This wax is similar in consistency to shoemakers' heel ball and is supplied commercially in an amorphous state. Some preliminary tests have been made on a lash-up rig by M.E. Dept. of the R.A.E. to break the wax down into spherical

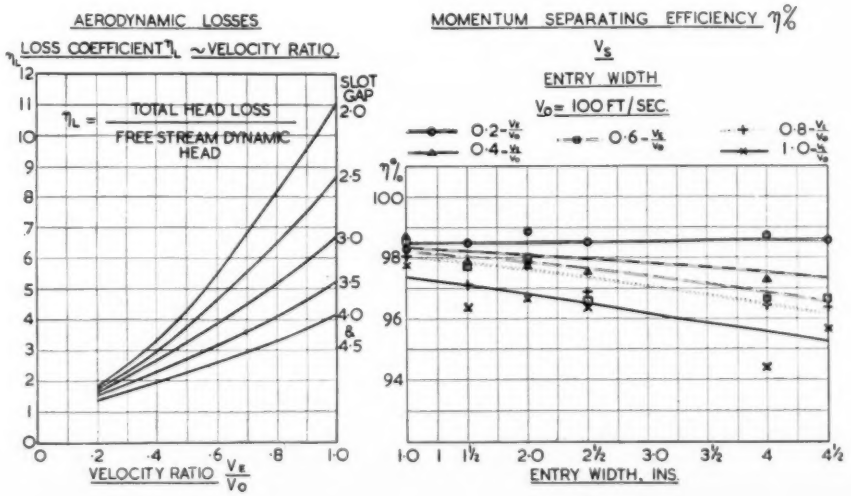

Fig. 7. Pneumatic and separating efficiencies of Naiad intake.

droplets. The technique of spraying the molten wax through an ordinary spray gun was discarded at an early date because the particles so obtained tended to be hollow and hence to have a false apparent density. A more promising line of attack explored by the R.A.E. is to centrifuge the particles from a heated spinning disc rotating at high speed and some success has been achieved. Fig. 8 shows the rig which is now under construction by Napiers based on this principle. A spinning disc of about 3 in. diameter is rotated by a Desoutter air-driven grinder up to 70,000 r.p.m., and is heated by an electrical resistance element consuming 500 watts. The heat input is controllable by a rheostat. The wax is melted in the 7-pint container above the disc and is allowed to drop on the disc through a regulating valve. The wax temperature in the container is thermostatically controlled. It has been found by the R.A.E. that the particles solidify by dropping through the air about 2 ft, and the spinning disc has therefore been surrounded by a conical container about 4 ft diameter. Although this test rig has not yet been put to use, some of the results obtained by the R.A.E. on a lash-up rig are illustrated in the microphotographs in Fig. 9. These results have been improved in preliminary experiments conducted by Napiers, and it is expected that the majority of particles will lie in the 25μ to 30μ range, thus closely simulating natural water droplets in cloud. The wax particles have been found to flow freely and the hopper/conveyor belt technique can be used in the same way as for sand.

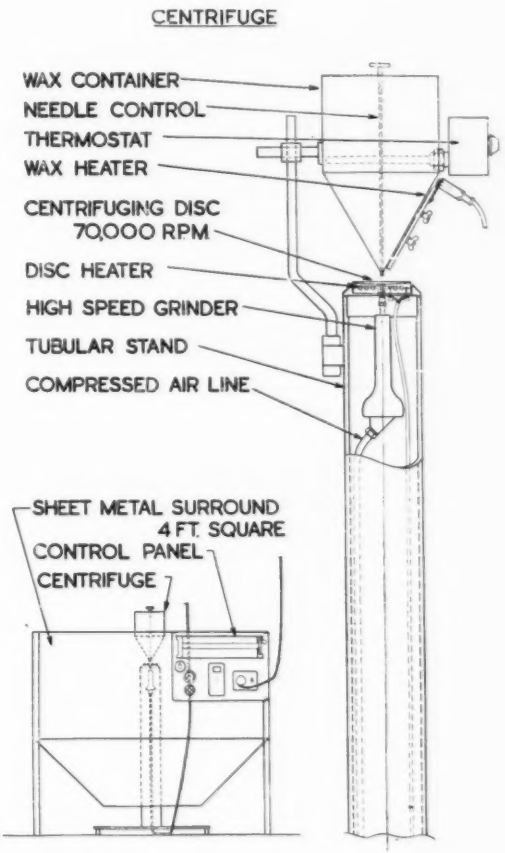

Fig. 8. Rotating disc apparatus for production of wax particles.

Fundamental Research

In the test programme just outlined it was felt that some doubt would be attached to the application of the test results to full-scale flight conditions. For this reason a programme of fundamental research has been started. A theoretical analysis has enabled this Company to isolate what is hoped are the fundamental variables governing the momentum separation, and calculations based on the theories developed have shown that for an intake of the ducted spinner side entry type a momentum cleaning efficiency of 87 per cent. for sand, 53 per cent. for 17μ water droplets, and 79 per cent. for 40μ water droplets, at an airspeed of 255 knots would be achieved. This speed of 255 knots is the speed to which the aeroplane would drop from a cruising speed of 270 knots with the full ramming intakes.

To confirm the theory built up for momentum separation, a test rig has been constructed in which it is hoped to check the main variables affecting the problem. This test rig, Fig. 10, consists of a rectangular working section wind tunnel with a square entry flush slot in the bottom wall. The tunnel section is 14 in. $\times$ 6 in. and has the flush entry in the short side. The width of entry in the direction of the airflow can be varied

from zero to 2 in. The entry at right-angles to the direction of the airflow has been divided into three parts, each part exhausting to an independent air measuring source and a filter bag so that the wall effects of the tunnel could be eliminated on the centre section. Just ahead of the slot is a boundary layer bleed to draw off any particles which may be carried along the floor of the tunnel and give a false answer. This also enables the thickness of boundary layer just ahead of the entry to be reduced. The theoretical investigation has shown that the efficiency of separation will be governed by the model Reynolds number, particle Reynolds number, and Weber number of the water droplets.

Different combinations of these non-dimensional quantities can be obtained by varying the tunnel speed, the entry velocity, the width of entry, the particle size and the particle density. Considerable effort has been made in trying to obtain materials which can be produced in small spherical particles and having specific gravities of the order of ·7, 1, and 1·2. So far the Carnauba Wax with a specific gravity of about 1, and White Ellesmere Wax with a specific gravity of about ·8, have been chosen as being most nearly satisfactory. Kallodoc powder with a specific gravity of about 1·2 may also be used in spite of its very high cost, and the fact that it is available only in fairly small quantities. The search for a range of particles is still going on. The use of solid particles to determine the effect of different variables on the efficiency of the separation will not be entirely representative of water droplets due to the fact that water droplets when subjected to large accelerations are distorted and consequently the drag coefficient is altered. The amount of distortion is a function of the Weber number, which is defined as :— $\frac{pV^2D}{\text{surface tension}}$.

It is realised that it would be extremely difficult to allow for this variable on the actual test rig, and it is proposed that the effect of this particular variable will be assessed by measuring the terminal velocities of liquid droplets of different surface tensions and from the measured terminal velocities calculating the drag coefficient. Experimental results on the model could then be modified by a factor obtained from this experiment. This is at present being examined by the R.A.E. in conjunction with Napiers.

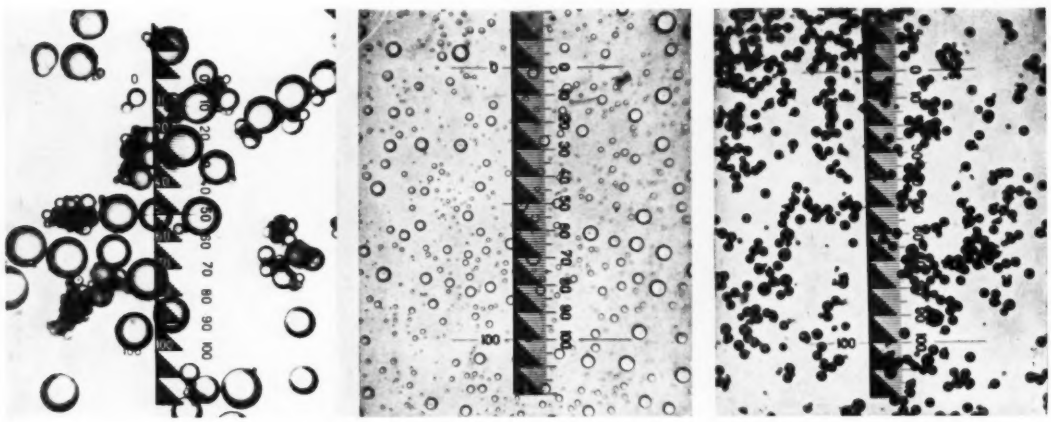

Fig. 9. Microphotographs of Kallodoc, water and wax particles.

Full-Scale Flight Research

Concurrently with this programme of laboratory research a flight programme is also in hand. This

flight programme is at present applicable to the Naiad engine only and consists of two parts :—

(*a*) The determination of the effect of icing conditions on the compressor and intake system of a Naiad engine.

(*b*) The full-scale flight testing of protective devices.

For the first part of the tests a Naiad engine with the turbine shaft and all compressor stages except the first removed is being fitted to a Lincoln flying test bed, with provision for spraying water ahead of the ducted spinner. The complete oil system with electric heaters to maintain the gearbox oil temperature at operational level is envisaged. The propeller will be controlled in the normal way by the C.S.U. so that the engine will be exactly similar to the full-scale engine up to the first compressor stage. The airflow through the engine would be maintained by the single compressor stage driven by the windmilling propeller through the normal reduction gears. The use of a part engine instead of a full scale engine operating under its own power is put forward for reasons of economy, as it is felt that considerable damage could occur from ice build-up in the engine intake, without any protective measures whatsoever.

Fig. 10. *Flush slot test rig.*

For the second part of the programme a complete engine with the protective devices available will be fitted in order to check the merits of different protective systems under icing conditions. Tests would subsequently be carried out under natural icing conditions with the spray nozzle equipment removed.

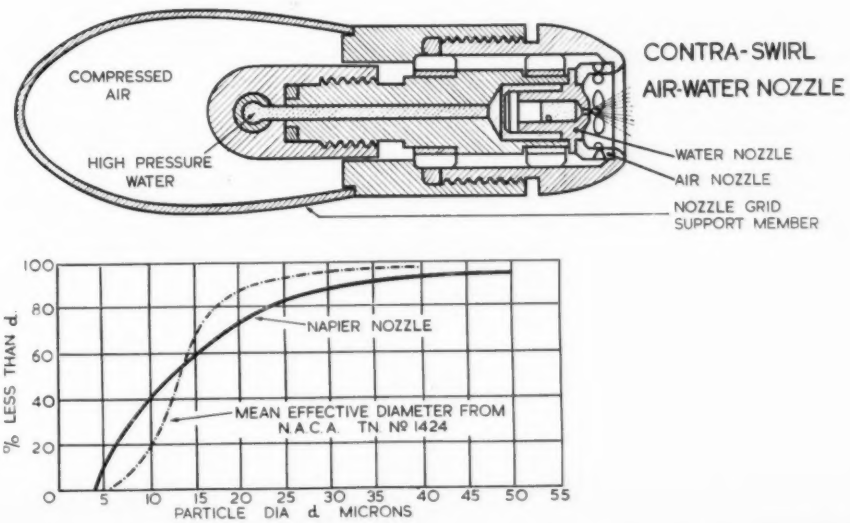

Fig. 11. *Water spray nozzle.*

To supplement the research work already carried out at the R.A.E. on the development of a suitable water spray nozzle, Napiers have undertaken further work at their request.

A compound air/water nozzle has been manufactured and tested to the design shown in Fig. 11. Water is supplied to the central nozzle under hydraulic pressure up to 1,000 lbs.inch^2 and a counter-swirling air nozzle is also provided taking air supply at 35 lbs.inch^2 pressure. Combinations of air and water nozzles with various flow numbers have been tested and the results are now being analysed. In general, particle size is not very sensitive to applied water pressure but no set law has been observed. However, it has been found that the smallest water nozzle with a flow number of ·13 combined with the smallest air nozzle gave the best combination, but the water flow rate was lower than that desired. Rig tests also indicated that the optimum air pressure was 20 lbs.inch^2.

A compromise has now been reached with a slightly bigger water nozzle ejecting 5 gallons per hour at 300 lbs.inch^2 pressure and the particle size obtained under static conditions is shown in the diagram. Curves are also included from N.A.C.A. Technical Note No. 1424, showing the observed size for the water droplets occurring under natural conditions.

Tests are proceeding to determine :—

(*a*) The possibility of recoalescence of water droplets from adjacent nozzles.

(*b*) The effect of the flight airstream in breaking down particle size.

The Author wishes to express his thanks to members of the staff of D. Napier & Son, Ltd., for their assistance in preparing this article.